3rd Quarterly Report - 4th Year
February 1 to April 30, 1953

ARC-CAST MOLYBDENUM-BASE ALLOYS

Contract N8onr-78700
Task Order N8onr-78701
Project NR 039-002

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Covering the Period February 1 to April 30, 1953

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to

Office of Naval Research
Navy Department

prepared by

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Climax Molybdenum Company of Michigan

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CONTRACT N8onr-78700
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INTRODUCTION

During the third quarter of the fourth year of Contract N8onr-78700, the study of mechanical properties of molybdenum-base alloys has been continued. Four 30-pound heats containing greater amounts of alloying elements than have been previously used in the program on mechanical properties have been prepared. The resulting ingots have been extruded and are in test. One 250-pound heat has been made to replace a molybdenum-zirconium heat that supplied insufficient stock for study.

The hardness and tensile strength of binary molybdenum-base alloys containing aluminum, cobalt, niobium, titanium, and vanadium have been determined from room temperature to 1600 F. The stress-rupture properties of the binary alloys have been determined at 1600, 1800, and 2000 F. Two of the alloys have exhibited outstanding high-temperature stress-rupture strength, namely, the 0.75% niobium and 1.26% titanium alloys. The 0.75% niobium alloy, in the stress-relieved condition, exhibited greater stress-rupture life than any other molybdenum-base alloy so far tested. The 1.26% titanium alloy, in the fully recrystallized condition, surpassed any other fully recrystallized molybdenum-base alloy so far tested.

Preliminary investigation of molybdenum-base ternary alloys has been started. A survey has been made of alloys containing 0.16% aluminum and increasing amounts of cobalt, niobium, titanium, vanadium, and zirconium as third elements.

In the study of deoxidation, 0.10% has been established as the minimum amount of aluminum for adequate deoxidation of "acceptable" molybdenum powder melted in argon. Further evaluation of thorium as a deoxidant has been made; the thorium was added in the form of both powder and sheet.

STUDY OF DEOXIDATION

In continuation of the study of deoxidation practice, seven ten-pound ingots were made in the powder machine and five six-pound ingots in the bar machine during the past quarter. This section of the report is primarily an enumeration of the processing data and properties of these ingots. The composition, melting class, ingot diameter, additions, chemical analysis, hardness, and bend ductility of each of the ingots are given in Table 1.

Since excess aluminum affects the properties of arc-cast molybdenum, experiments were run to determine the minimum aluminum addition required to effect adequate deoxidation of a powder charge melted in argon. The oxygen contents of different lots of "acceptable" molybdenum powder vary from 0.010 to 0.04% as determined by the loss of weight in dry hydrogen at 1950 F, and it would be expected that the minimum aluminum addition would depend upon the oxygen content of the powder. Four powder-machine heats were melted from a single lot of powder, which had a loss of weight in dry hydrogen equal to 0.023%. The amounts of aluminum added were 0.03, 0.05, 0.10, and 0.15%, respectively.

The fifth powder-machine heat (1205) was a carbon-vacuum heat to which less carbon was added than is normally required for full deoxidation. A small amount of zirconium (0.05%) was added to complete the deoxidation, since in heats made earlier under this contract it had been noted that little or no speckling was evident on the fracture surfaces or in the microstructure when zirconium (or titanium) was added to carbon-vacuum molybdenum.

Two ten-pound heats (1209, 1210) were made to provide experience in deoxidizing nickel-molybdenum alloys, with a view towards producing a large ingot for determination of mechanical properties. One was deoxidized with carbon in vacuum, the other with aluminum in argon.

The last five heats of Table 1 were six-pound heats made in the bar machine. Ingot B183 was made from molybdenum-aluminum bar stock that had been melted in argon and subsequently worked. The bar stock was remelted in vacuum, in an attempt to remove the residual aluminum and aluminum oxide by vaporization and thus obtain carbon-free unalloyed molybdenum of high purity.

Heats B184, B185, B196, and B197 were a series of heats deoxidized with thorium, 0.07% (vacuum), 0.07% (argon), 0.10% (argon), and 0.3% (vacuum), respectively. The thorium was added to the first two heats in the form of powder and to the last two in the form of chips from thorium sheet.

Macrostructure

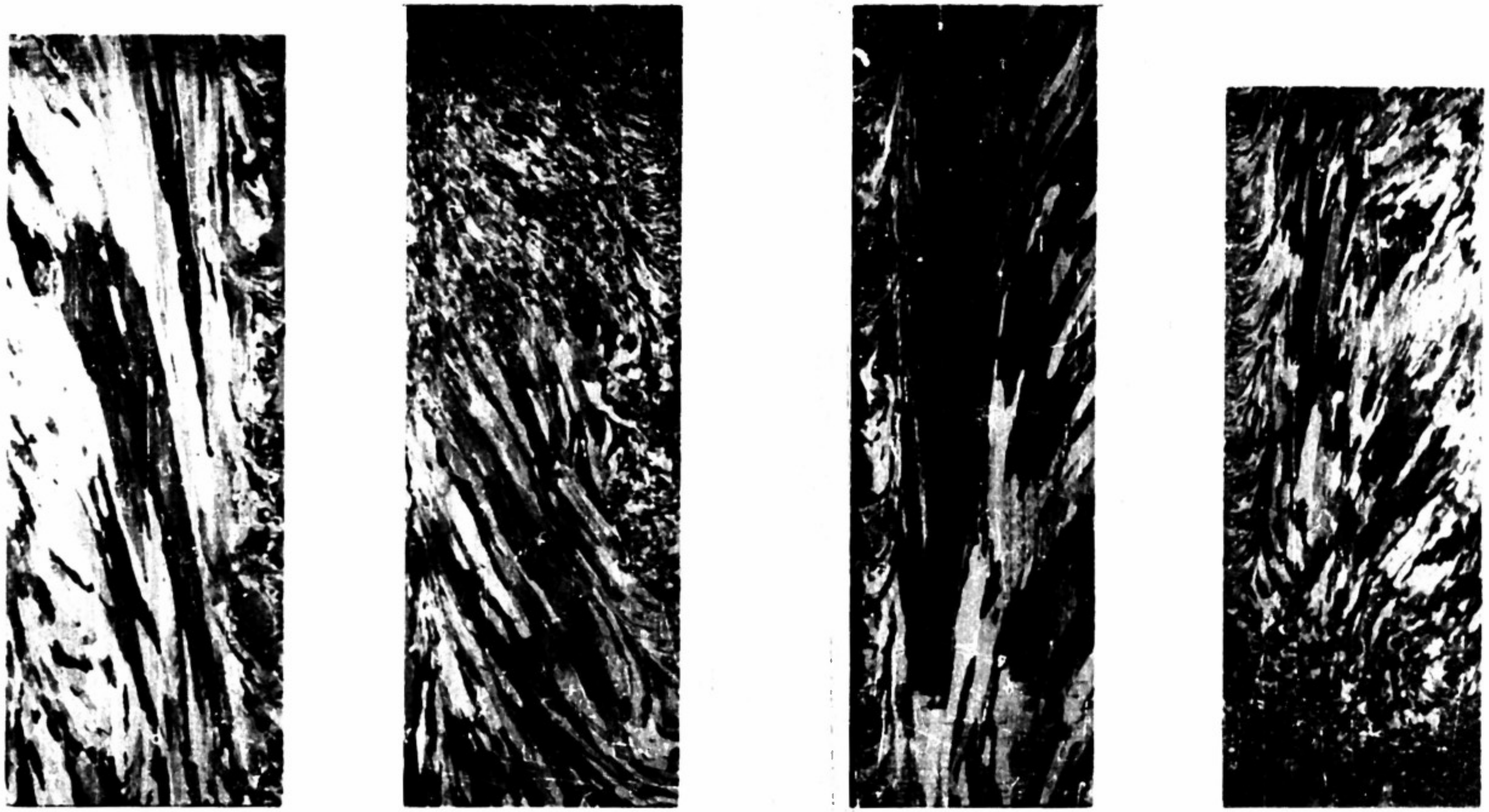
The macrostructures of the ten-pound ingots of Table 1 are shown in Figures 1-2. The surfaces of the ingots deoxidized with 0.03 and 0.05% aluminum and the nickel-molybdenum ingot cast in argon were corrugated and folded. Macroporosity was observed in the ingots deoxidized with 0.03 and 0.05% aluminum and in the nickel-molybdenum ingot cast in vacuum. In the aluminum series of ingots the porosity decreased as the added amount of aluminum was increased.

TABLE 1

ADDITIONAL INGOTS FOR DEOXIDATION PROGRAM

Heat	Melting Class*	Melting Atm.	Ingot Dia, in.	Additions %	Chemical Analyses %	Hardness As Cast VPN	Bend Angle Degrees Long.	Trans.
10-Pound Ingots								
1201	4	argon	3	0.03 Al	0.002 C 0.012 Al	185	-	-
1202	4	argon	3	0.05 Al	0.002 C 0.027 Al	185	1.2	-
1203	4	argon	3	0.10 Al	0.002 C 0.076 Al	152	39	4
1204	4	argon	3	0.15 Al	0.003 C 0.12 Al	177	27	5
1205	1	vacuum	3	0.027 C 0.05 Zr	0.010 C 0.056 Zr	179	68	33
1209	1	vacuum	3	0.042 C 0.15 Ni	0.025 C	167	-	-
1210	4	argon	3	0.2 Al 0.15 Ni	0.003 C 0.16 Al 0.13 Ni	181	7	-
6-Pound Ingots								
B183 (Remelt)	2	vacuum	2	0.004 C 0.18 Al		176		
B184	1	vacuum	2	0.033 C 0.07 Th	0.033 C 0.091 Th	183		
B185	3	argon	2	0.033 C 0.07 Th	0.031 C 0.004 Th	189		
B196	3	argon	2	0.033 C 0.10 Th		181		
B197	1	vacuum	2	0.033 C 0.30 Th		179		

* Melting Classes: (1) carbon-vacuum, (2) vacuum, no carbon added, (3) carbon-argon, (4) argon, no carbon added



INGOT 1201
0.002% CARBON
0.012% ALUMINUM
CAST IN ARGON

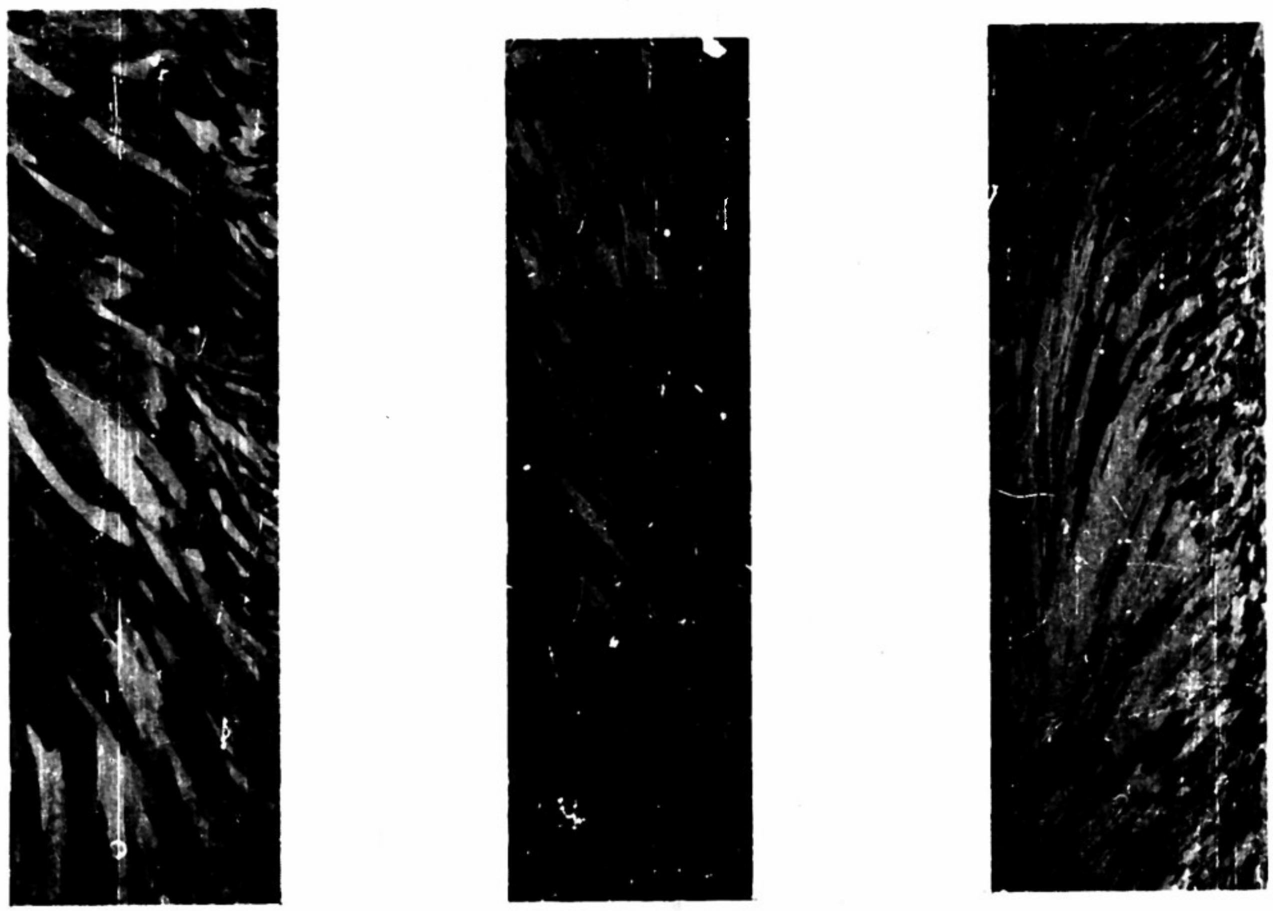
INGOT 1202
0.002% CARBON
0.027% ALUMINUM
CAST IN ARGON

INGOT 1203
0.002% CARBON
0.076% ALUMINUM
CAST IN ARGON

INGOT 1204
0.003% CARBON
0.12% ALUMINUM
CAST IN ARGON

FIGURE 1 -- MACROSTRUCTURES OF INGOTS DEOXIDIZED WITH ALUMINUM, X1

(P971)



INGOT 1205

0.010% CARBON
0.050% ZIRCONIUM
CAST IN VACUUM

INGOT 1209

0.025% CARBON
0.15% NICKEL ADDED
CAST IN VACUUM

INGOT 1210

0.003% CARBON
0.16% ALUMINUM
0.13% NICKEL
CAST IN ARGON

FIGURE 2 — MACROSTRUCTURES OF INGOT DEOXIDIZED WITH ZIRCONIUM AND OF NICKEL—MOLYBDENUM INGOTS, X1

(P972)

The bar-machine heats all filled the mold well except Heat B185; the arc was difficult to control during melting of this heat, and the result was a porous casting. The grain sizes of the four ingots to which thorium was added were slightly finer than that of carbon-vacuum molybdenum. The molybdenum-aluminum alloy bar melted in vacuum had the same grain size as a normal carbon-vacuum ingot.

Microstructure

The microstructures of the ingots in the series deoxidized with aluminum are shown in Figures 3-6. Platelike oxide and speckling were evident on the fractures of the ingots melted from charges containing 0.03% and 0.05% aluminum, respectively. This condition was particularly severe in the ingot treated with only 0.03% aluminum. Oxide also appeared in the photomicrographs. The ingots to which 0.10% and 0.15% aluminum were added were totally devoid of speckling but exhibited microporosity. On the basis of examination of the microstructure, the minimum amount of aluminum for deoxidation is about 0.10%. Heat 1203, treated with 0.10% aluminum, produced the lowest as-cast hardness, 152 VPN.

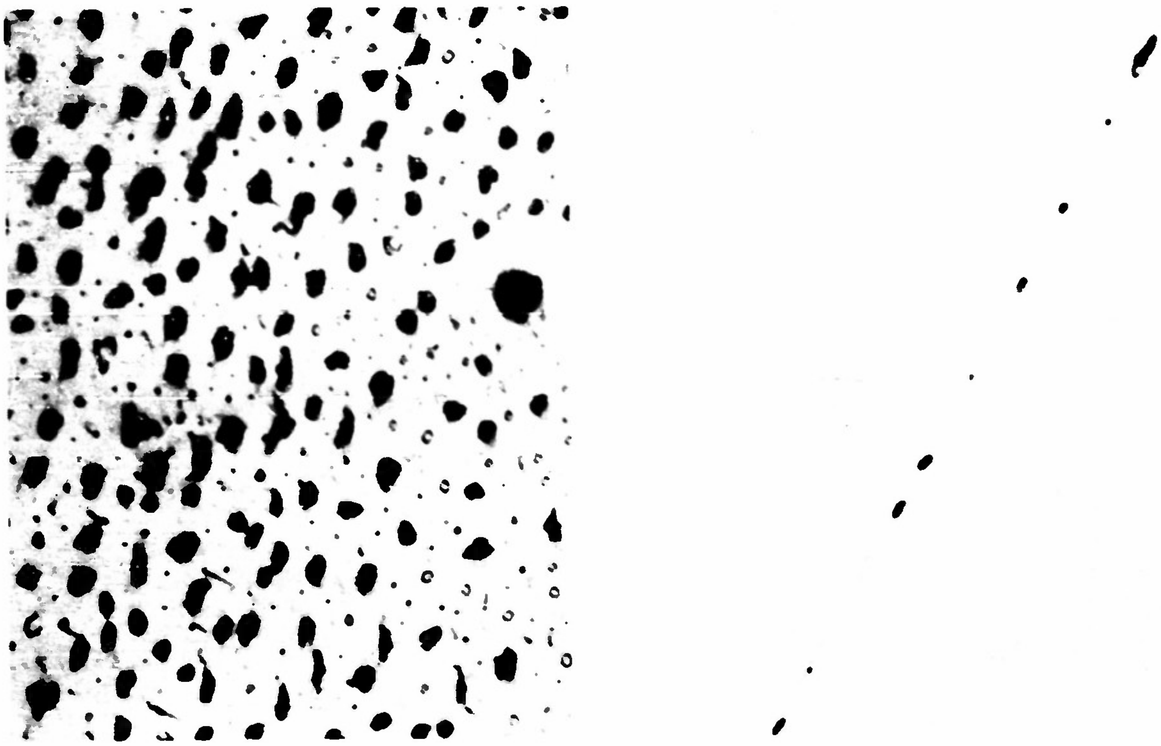
The small amount of zirconium added to Heat 1205 apparently aided deoxidation. A little speckling was evident on the fracture but not in the microstructure, Figure 7. There was far less speckling or oxide than would be expected in a corresponding carbon-vacuum ingot made without the addition of zirconium.

Both the fractures and microstructures of the molybdenum-base nickel alloys were free from speckling and oxide, Figures 8-9. On the basis of microstructure alone, it can be said that melting and deoxidation were successful.

The microstructure of ingots deoxidized with aluminum in argon atmosphere is essentially single phase, Figures 5-6. Nevertheless, some of the aluminum remaining in the ingot is in the form of aluminum oxide. Since the oxide is not visible under the microscope, it is assumed to be in solid solution in the molybdenum. Remelting this type of ingot (B183) produced a microstructure containing platelike oxide and speckling, Figure 10. The melting process was not oxidizing, as witnessed by the fact that carbon-vacuum bars remelted in the same system did not lose carbon. It has been difficult, therefore, to trace the source of the platelike oxide in the remelted, aluminum-bearing heat.

In the thorium series, the ingot deoxidized in vacuum with 0.07% thorium added as powder contained platelike oxide of a somewhat different appearance than the molybdenum oxide normally observed. The platelike constituent is therefore considered to be thorium oxide, Figure 11. The photomicrograph was taken to show this oxide specifically and is not representative of the typical microstructure. The ingot deoxidized with 0.07% thorium powder in argon contained neither oxide nor speckling, but carbide, Figure 12.

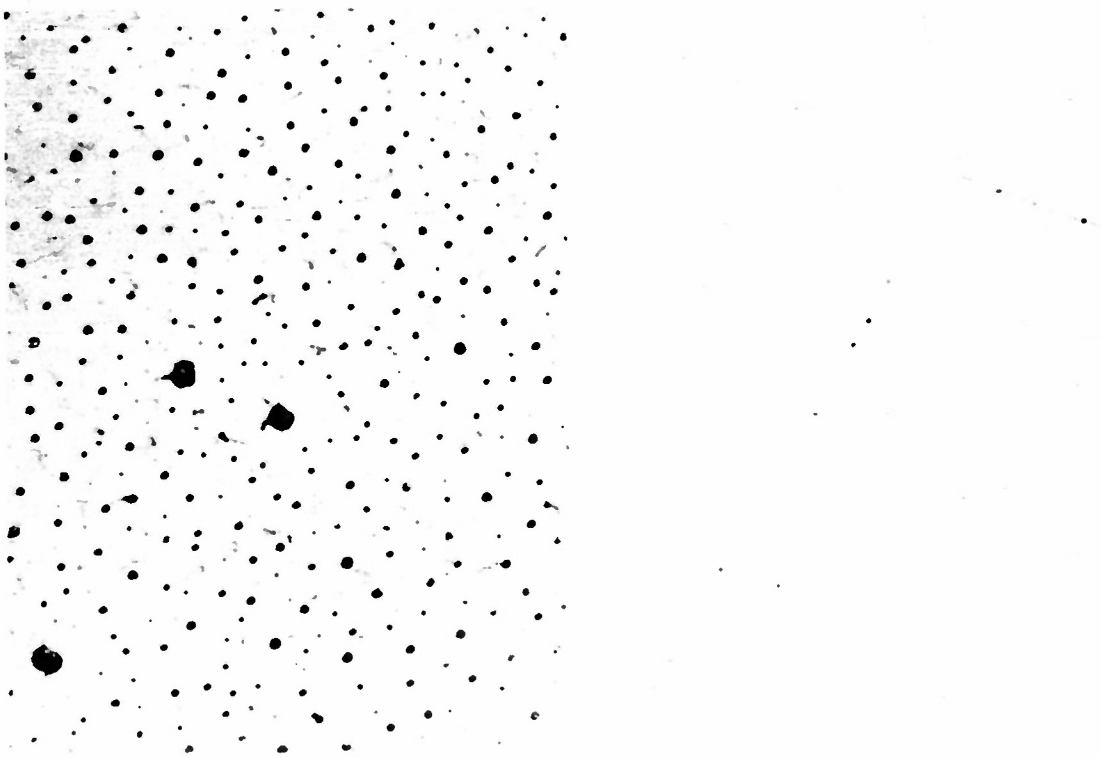
The two heats made with thorium in the form of sheet contained large amounts of what is believed to be thorium oxide on the fractures and in the grain boundaries, Figures 13-14. The grain boundary constituent is considered to be oxide because it was readily observed in unetched specimens. The thorium sheet used in making the two heats was thoroughly cleaned in a mixture of hydrofluoric and nitric acids, but apparently contained a considerable amount of oxygen, since so much oxide remained in the heats to which it was added and so little remained in the heats to which thorium powder was added.



(A) FRACTOGRAPH, X2000 (M2619)   (B) ELECTROPOLISHED, X2000 (M2694)

FIGURE 3 – MICROSTRUCTURE OF INGOT 1201

0.002% CARBON, 0.012% ALUMINUM, CAST IN ARGON
(0.03% ALUMINUM ADDED)



(A) FRACTOGRAPH, X2000 (M2659)   (B) ELECTROPOLISHED, X2000 (M2681)

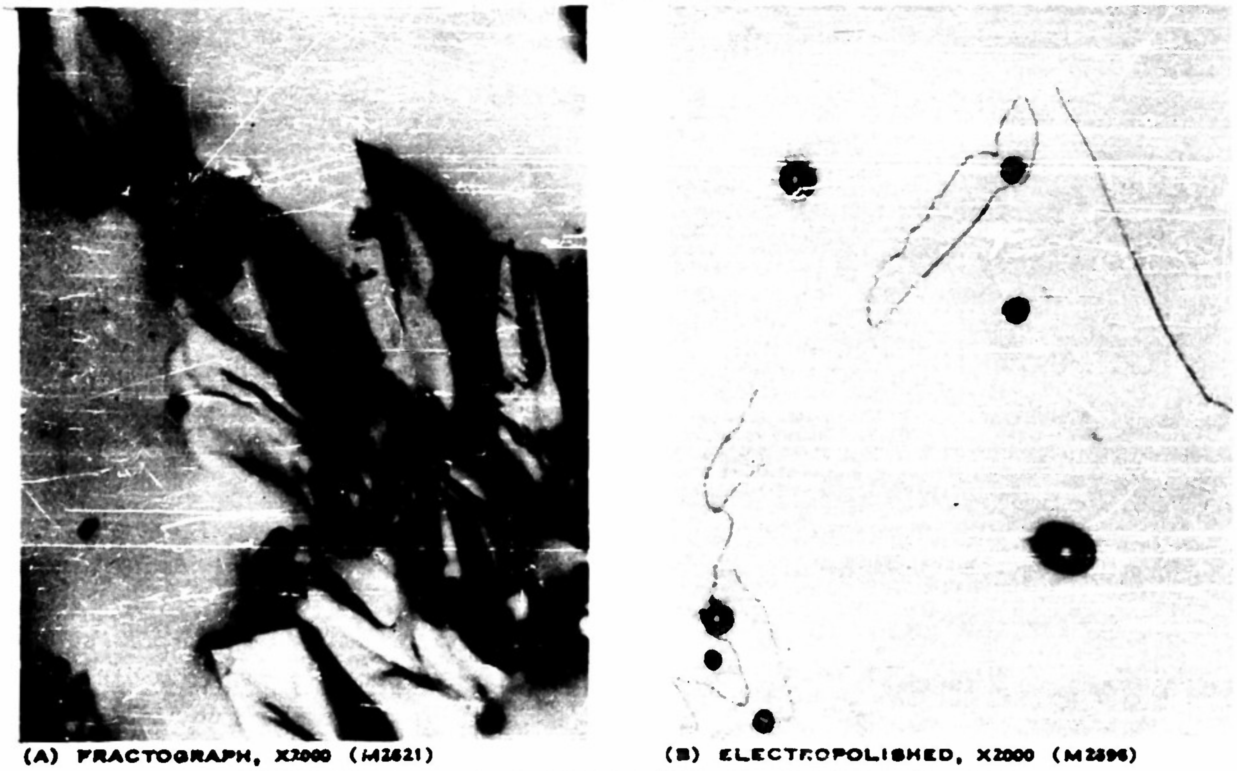
FIGURE 4 – MICROSTRUCTURE OF INGOT 1202

0.002% CARBON, 0.027% ALUMINUM, CAST IN ARGON
(0.05% ALUMINUM ADDED)

(A) FRACTOGRAPH, X2000 (M2820)   (B) ELECTROPOLISHED, X2000 (M2595)

FIGURE 5 — MICROSTRUCTURE OF INGOT 1203

0.002% CARBON, 0.076% ALUMINUM, CAST IN ARGON
(0.10% ALUMINUM ADDED)



(A) FRACTOGRAPH, X2000 (M2621)   (B) ELECTROPOLISHED, X2000 (M2596)

FIGURE 6 — MICROSTRUCTURE OF INGOT 1204

0.003% CARBON, 0.12% ALUMINUM, CAST IN ARGON
(0.15% ALUMINUM ADDED)

(A) FRACTOGRAPH, X2000 (M2622) (B) ELECTROPOLISHED, X2000 (M2880)

FIGURE 7 — MICROSTRUCTURE OF INGOT 1205

0.010% CARBON, 0.056% ZIRCONIUM, CAST IN VACUUM

(A) FRACTOGRAPH, X2000 (M2624) (B) ELECTROPOLISHED, X2000 (M2898)

FIGURE 8 — MICROSTRUCTURE OF INGOT 1209

0.025% CARBON, 0.15% NICKEL ADDED, CAST IN VACUUM

(A) FRACTOGRAPH, X2000 (M2625) (B) ELECTROPOLISHED, X2000 (M2692)

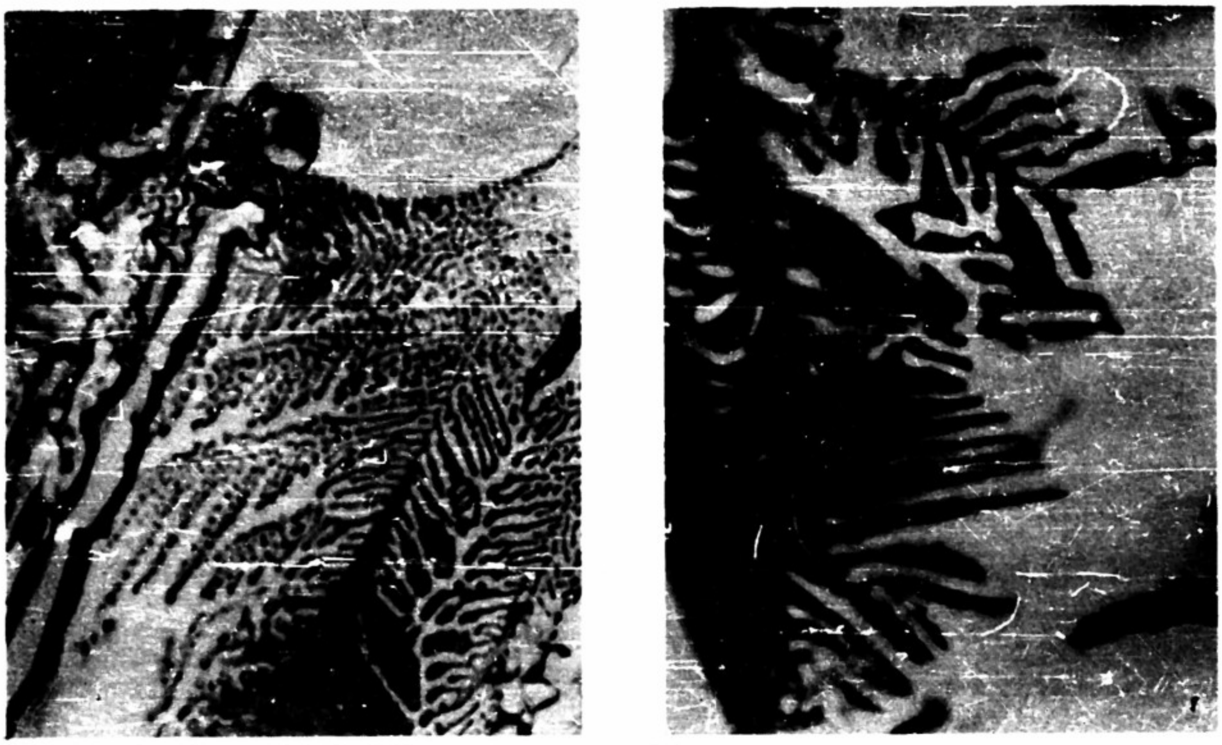
FIGURE 9 — MICROSTRUCTURE OF INGOT 1210

0.003% CARBON, 0.16% ALUMINUM, 0.13% NICKEL, CAST IN ARGON

FRACTOGRAPH, X2000 (M2613)

FIGURE 10 — MICROSTRUCTURE OF INGOT B183

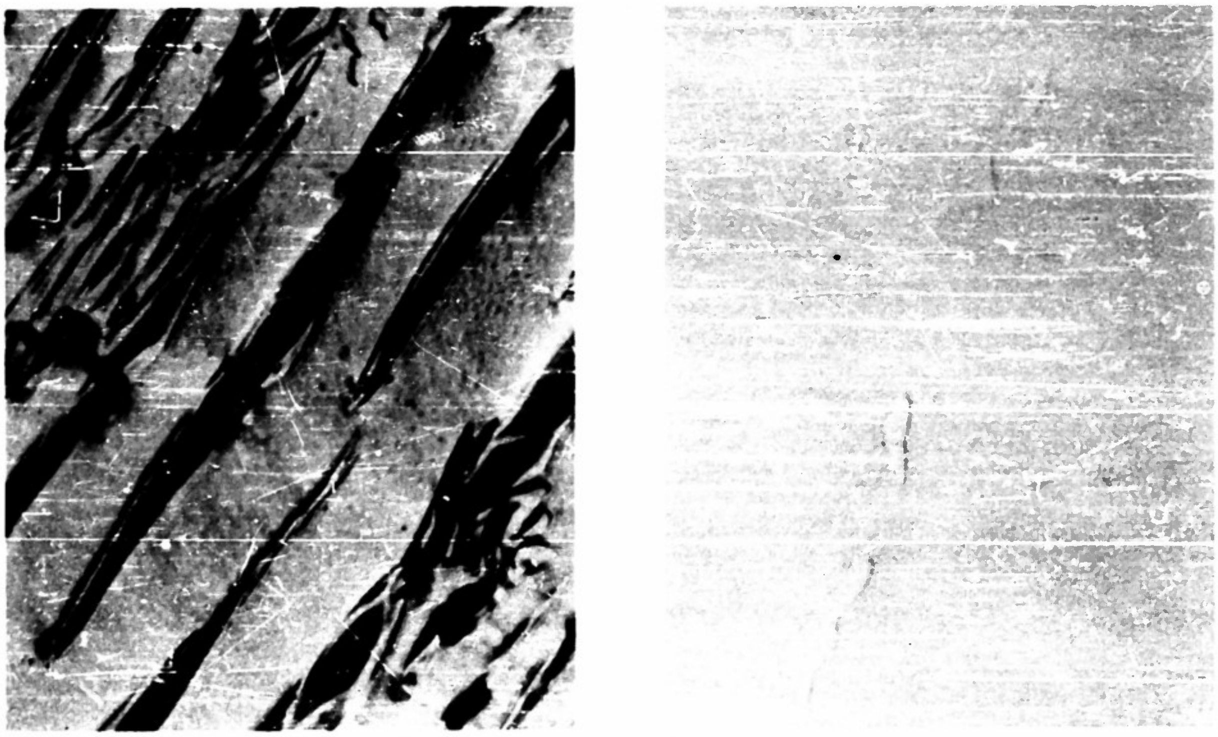
PRODUCED BY REMELTING IN VACUUM A BAR OF ALUMINUM-KILLED, ARGON-MELTED, ARC-CAST MOLYBDENUM CONTAINING 0.004% CARBON AND 0.18% ALUMINUM



(A) FRACTOGRAPH, X2000 (M2680) (B) ELECTROPOLISHED, X2000 (M2683)

FIGURE 11 — MICROSTRUCTURE OF INGOT B184

0.033% CARBON, 0.091% THORIUM, CAST IN VACUUM



(A) FRACTOGRAPH, X2000 (M2675) (B) ELECTROPOLISHED, X2000 (M2699)

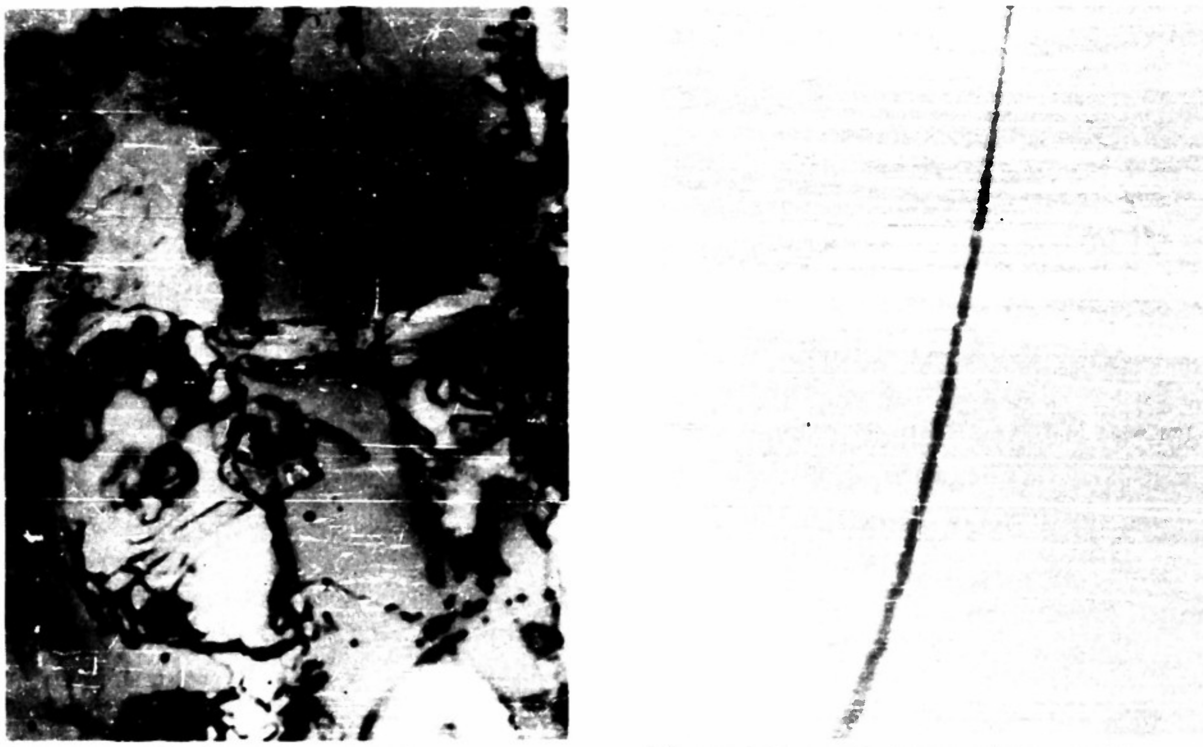
FIGURE 12 — MICROSTRUCTURE OF INGOT B185

0.031% CARBON, 0.004% THORIUM, CAST IN ARGON

(A) FRACTOGRAPH, X2000 (M2916) (B) POLISH-ETCH-BUFF, X2000 (M2887)

FIGURE 13 — MICROSTRUCTURE OF INGOT B196

0.033% CARBON AND 0.10% THORIUM ADDED, CAST IN ARGON



(A) FRACTOGRAPH, X2000 (M2802) (B) POLISH-ETCH-BUFF, X2000 (M2888)

FIGURE 14 — MICROSTRUCTURE OF INGOT B197

0.033% CARBON AND 0.30% THORIUM ADDED, CAST IN VACUUM

Bend Ductility as Cast

The longitudinal and transverse bend ductilities of the ten-pound ingots are given in Table 1. These were determined by the test described in the third annual report. Longitudinal specimens were cut with the grain and transverse specimens across the grain; the deflection rate for all of the tests was 0.005 inch per minute. The agreement between ductility, especially in the transverse test, and forgeability was satisfactory. Good forgeability accompanied good bend ductility and vice versa.

The high value for transverse ductility of the carbon-vacuum heat containing a small amount of zirconium is noteworthy and confirms data published in the third annual report.

Forging Tests

Cylinders, 1" diameter x 1" long, from the ingots of Table 1 were subjected to the forging test described in the first quarterly report. The upset cylinders are shown in Figures 15-16.

Forging of the specimens from the series of heats deoxidized with increasing amounts of aluminum was about as expected from examination of the cast microstructure. All specimens from Ingot 1201 cracked; the specimen from Ingot 1202 forged at 2300 F also cracked. The cylinder from Ingot 1202 forged satisfactorily at 2000 F. The specimens from ingots deoxidized with 0.10% and 0.15% aluminum forged well; the ingot to which zirconium was added also forged satisfactorily.

Contrary to expectation after examination of the microstructure, the molybdenum-base nickel alloys did not forge well. It is possible that they could have been forged at a higher temperature. Forging tests were not made on Ingot 1209 because of the porosity of the ingot. During machining of Ingot 1210 it was noted that there was poor cohesion between the grains. Although the microstructures of these two ingots were clean, macroporosity was observed in Ingot 1209 and microporosity in Ingot 1210. Inasmuch as the two nickel-containing heats were comparatively new alloys from the point of view of melting in the powder machine, the defects in these heats are thought to have been due more to inexperience in melting than to improper deoxidation. Undoubtedly, further experience in handling and melting the alloy powder will result in ingots of better quality.

The remelted ingot (B183) did not forge well. This result was expected from the appearance of the microstructure.

Of the heats made with thorium powder (B184, B185), the one melted in argon forged better than the one melted in vacuum. Both heats made with chips from sheet thorium were unforgeable. Undoubtedly this behavior is associated with the high oxide content at the grain bounderies, Figures 13-14.

INGOT 1201
0.002% CARBON
0.012% ALUMINUM
CAST IN ARGON

INGOT 1202
0.002% CARBON
0.027% ALUMINUM
CAST IN ARGON

INGOT 1203
0.002% CARBON
0.076% ALUMINUM
CAST IN ARGON

INGOT 1204
0.003% CARBON
0.12% ALUMINUM
CAST IN ARGON

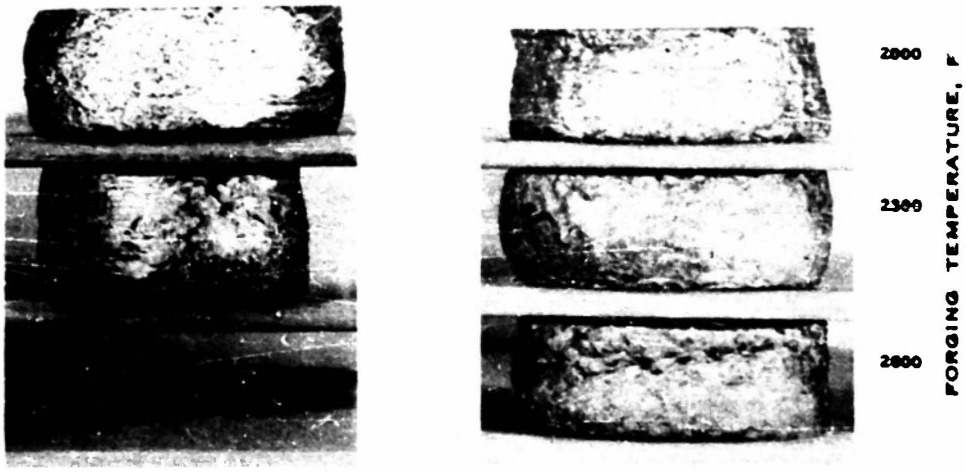
(P979)

INGOT 1205
0.010% CARBON
0.056% ZIRCONIUM
CAST IN VACUUM
(P980)

INGOT 1210
0.003% CARBON
0.16% ALUMINUM
0.13% NICKEL
CAST IN ARGON
(P980)

INGOT B183
0.004% CARBON ADDED
0.18% ALUMINUM ADDED
CAST IN VACUUM
(P982)

FIGURE 15 – CYLINDERS UPSET 50% IN SEVERAL STEPS



INGOT B184

0.033% CARBON
0.091% THORIUM
CAST IN VACUUM
(P982)

INGOT B185

0.031% CARBON
0.004% THORIUM
CAST IN ARGON
(P980)

INGOT B196

0.033% CARBON ADDED
0.10% THORIUM ADDED
CAST IN ARGON
(P995)

INGOT B197

0.033% CARBON ADDED
0.30% THORIUM ADDED
CAST IN VACUUM
(P995)

FIGURE 16 — CYLINDERS UPSET 50% IN SEVERAL STEPS

MECHANICAL PROPERTIES OF BINARY ALLOYS

In continuation of the study of mechanical properties of molybdenum-base alloys in the wrought condition, five ingots have been prepared since the last quarterly report. One of these was cast in a 7-1/2" diameter mold and weighed 220 pounds. The others were cast in a 4" diameter mold and weighed about 30 pounds each. The chemical compositions, melting data, hardness, and bend ductility of each of these ingots are given in Table 2.

TABLE 2

INGOTS FOR EXTRUSION AND DETERMINATION OF MECHANICAL PROPERTIES

Heat	Melting Class*	Melting Atm.	Ingot Dia, in.	Additions %	Analyses %	Hardness As Cast VPN	Bend Angle Degrees Long.	Bend Angle Degrees Trans.
1173	1	vacuum	4	0.046 C 0.50 Co	0.037 C 0.19 Co	185	1	1
1174	1	vacuum	4	0.043 C 4.20 Ti	0.027 C 3.59 Ti	232	18	4
1175	1	vacuum	4	0.043 C 1.62 V	0.033 C 1.46 V	189	25	6
1176	4	argon	4	1.7 Al	1.43 Al	292	19	1
1207	1	vacuum	7-1/2	0.036 C 0.09 Zr	0.019 C 0.09 Zr			

* Melting Classes: (1) carbon-vacuum, (2) vacuum, no carbon added, (3) carbon-argon, (4) argon, no carbon added

The 30-pound ingots contained a greater percentage of alloying element than previous heats which did not extrude well on a 2500-ton extrusion press at 2600 F. Recently a smaller, full-eccentric type of extrusion press has become available to this project. It was used for extruding these higher alloy ingots. The press is described in a later paragraph.

The room temperature hardnesses of the five ingots as cast agreed with the hardnesses of corresponding compositions given in the second annual report. The 3.59% titanium and the 1.43% aluminum alloys, like the high-titanium and high-aluminum alloys reported previously, exhibited greater bend ductility than the other molybdenum-base alloys tested.

Macrostructure as Cast

The macrostructures of the 30-pound ingots and a macrostructure typical of 200-pound ingots are shown in Figure 17. The section from the 200-pound ingot was taken from Ingot 1132, from which a center slice could be spared. In composition and macrostructure, Ingot 1132 was similar to Ingot 1008 of the first quarterly report.

In general, the grain sizes of the 30-pound alloy heats were finer than that of similar heats of unalloyed molybdenum. In macrostructure the 0.19% cobalt alloy (1173) was like that of the cobalt alloy (949) described in the third annual report. The 3.59% titanium alloy (1174) was somewhat finer grained than the 0.45% titanium alloy (1132), and the 1.46% vanadium alloy (1175) was comparable to the alloys containing less vanadium (1013, 1014) which were described in the first quarterly report. The 1.43% aluminum alloy (1176) was slightly finer grained than the 0.55% aluminum alloy (942) previously reported.

All of the ingots of the present series filled the mold well and were devoid of macroporosity.

Microstructure as Cast

Both the fracture and the microstructure of the 0.19% cobalt alloy were devoid of speckling, Figure 18. In this respect this alloy was much cleaner than the cobalt alloy (1145) of the second quarterly report.

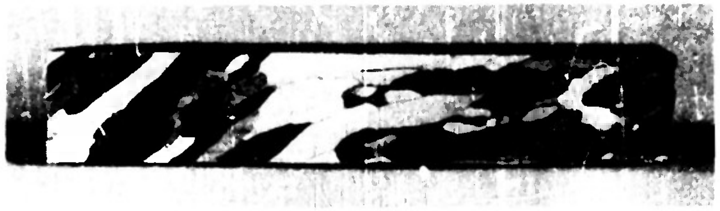
No fractograph was obtained from the 3.59% titanium ingot because of the difficulty in finding fracture facets in well deoxidized molybdenum-titanium ingots, as described in earlier reports. The characteristic fine carbide precipitate within the grains of the high-titanium alloys is shown in Figure 19. The specimen was etched; the structure is not apparent in the unetched condition.

The structures of the 1.46% vanadium, 1.43% aluminum, and 0.09% zirconium alloys were identical to those shown in the first quarterly reports for Ingots 1053, 983, and 1062, respectively.

Extrusion

As a datum material with which to compare the 1" diameter extruded and rolled bars, a 1" diameter bar of unalloyed molybdenum deoxidized with carbon in vacuum was selected. This bar had been processed in a manner similar to that shown in flow sheets for the various alloys. The cast ingot was extruded to 3-1/2" diameter at 2300 F; the extrusion was straightened, machined for rolling, annealed at 2600 F, and then rolled at 2200-1900 F to 1" diameter.

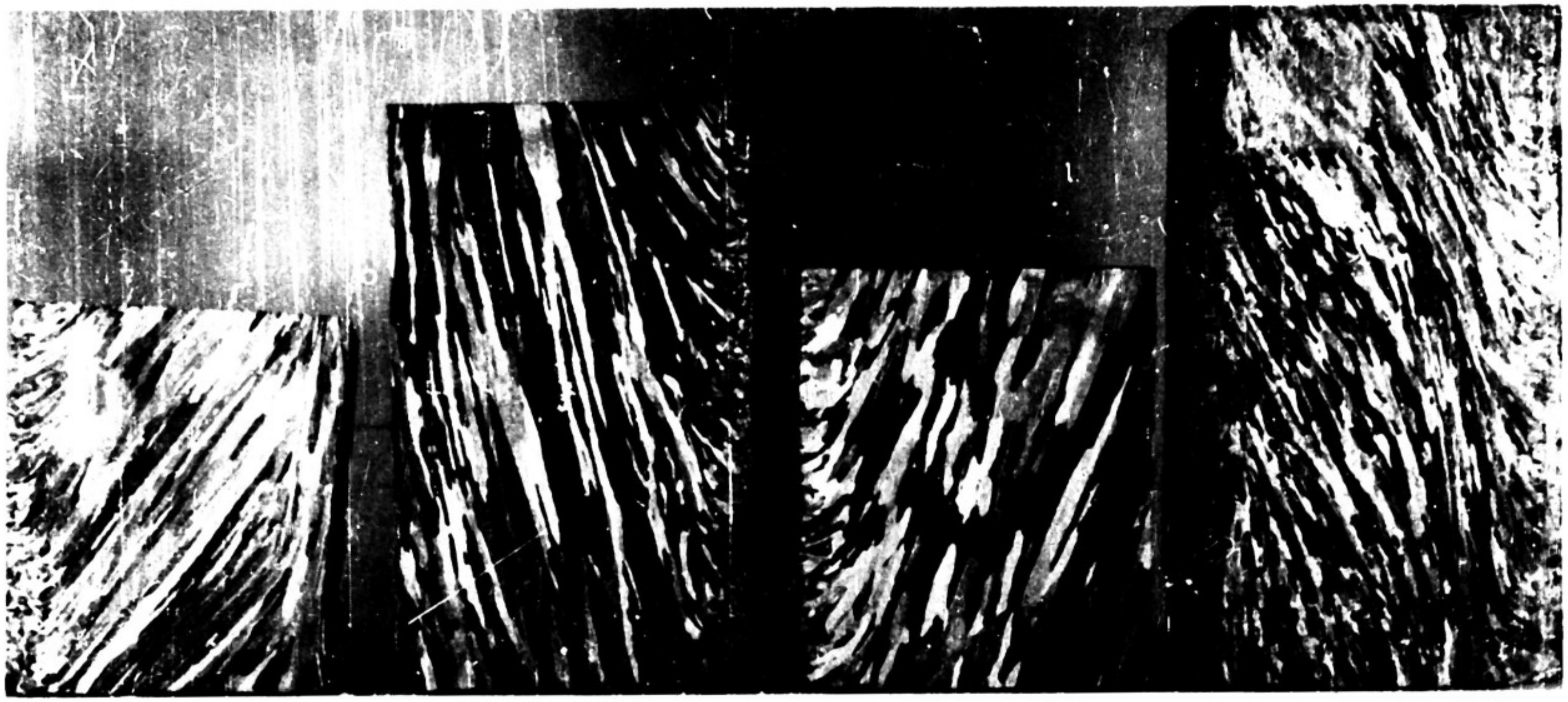
Rolling of the extrusions described in the last quarterly report (p 41) has now been completed. Of the seventeen extrusions of Group 2, five were rolled successfully to 5/8" and 1" diameter rounds, and the processing of these is given in flow sheets, Figures 20-24.



INGOT 1132
0.024% CARBON
0.46% TITANIUM
CAST IN VACUUM
(P969)

EDGE CENTER

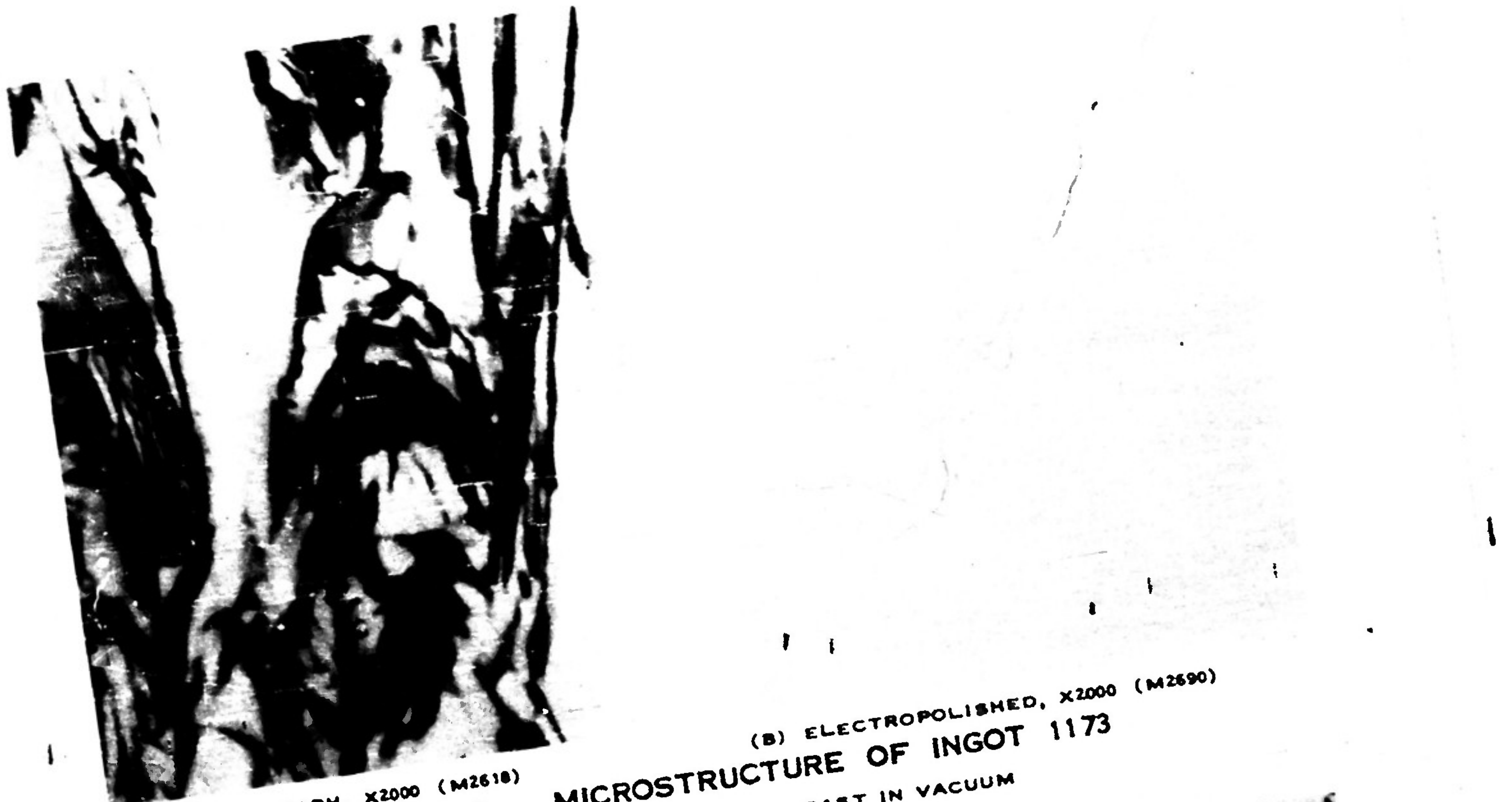
MACROSTRUCTURE TYPICAL OF 7-1/2" DIAMETER INGOT



(P970)

INGOT 1173	INGOT 1174	INGOT 1175	INGOT 1176
0.037% CARBON	0.027% CARBON	0.033% CARBON	1.43% ALUMINUM
0.19% COBALT	3.59% TITANIUM	1.46% VANADIUM	CAST IN ARGON
CAST IN VACUUM	CAST IN VACUUM	CAST IN VACUUM	

FIGURE 17 — MACROSTRUCTURES OF INGOTS FOR MECHANICAL PROPERTY STUDIES, X1

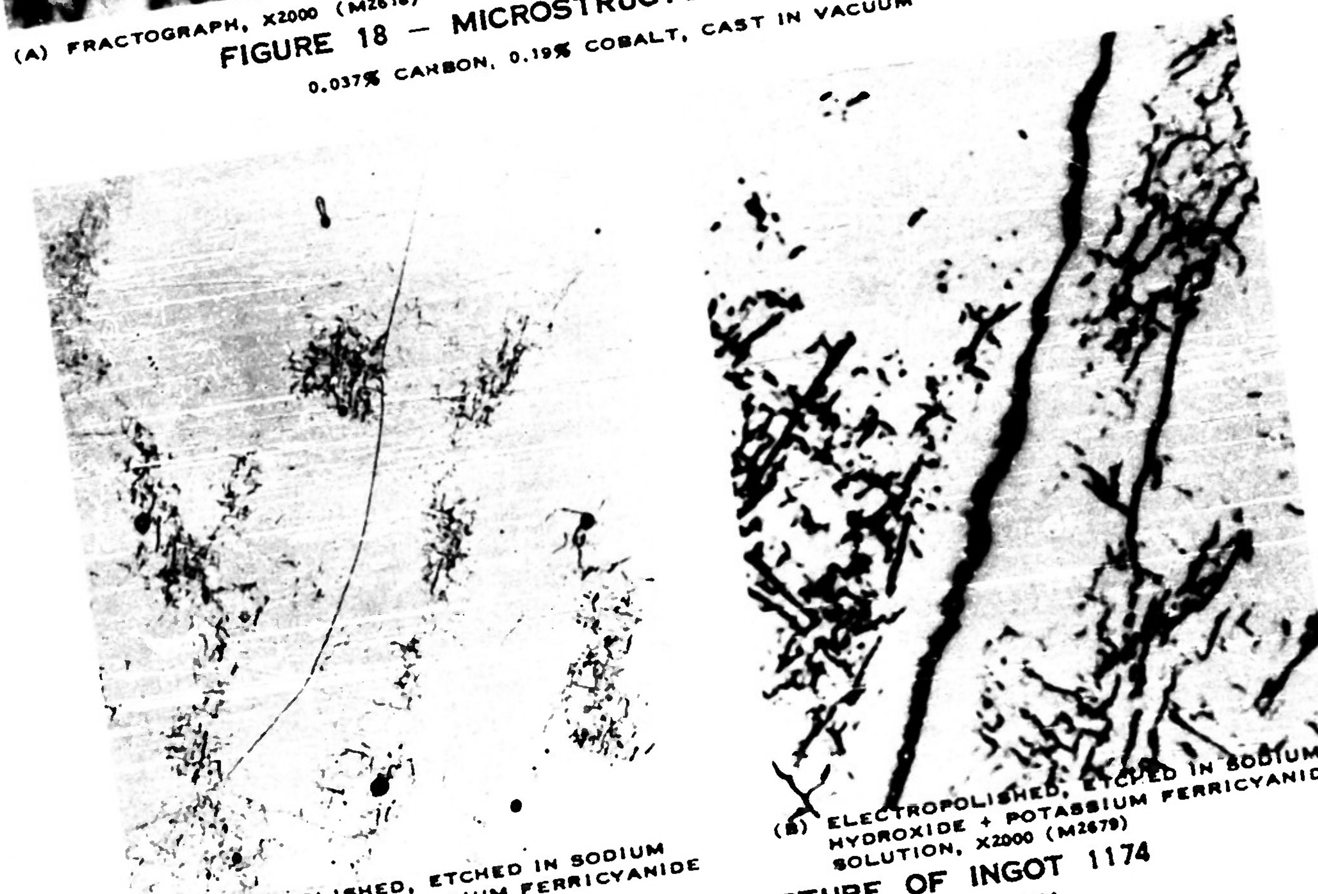


(A) FRACTOGRAPH, X2000 (M2618)

(B) ELECTROPOLISHED, X2000 (M2690)

FIGURE 18 — MICROSTRUCTURE OF INGOT 1173

0.037% CARBON, 0.19% COBALT, CAST IN VACUUM



(A) ELECTROPOLISHED, ETCHED IN SODIUM HYDROXIDE + POTASSIUM FERRICYANIDE SOLUTION, X250 (M2678)

(B) ELECTROPOLISHED, ETCHED IN SODIUM HYDROXIDE + POTASSIUM FERRICYANIDE SOLUTION, X2000 (M2679)

FIGURE 19 — MICROSTRUCTURE OF INGOT 1174

0.027% CARBON, 3.59% TITANIUM, CAST IN VACUUM

Ingot 1147, which had failed to extrude because of lack of lubrication, was remachined and re-extruded. The resulting extrusion was badly cracked. Ordinarily, if a molybdenum-base alloy ingot fails to go through the press on the first attempt--whatever the reason--microcracks arise, which are rapidly propagated upon the second attempt at extrusion. In the present instance cracking is not attributed to high alloy content but rather to the fact that re-extrusion was attempted.

Ingot 1150 stopped the press on the first attempt and upon sectioning was found to be badly cracked.

A sound piece of the 0.81% aluminum extrusion (1059), 3-3/4" diameter x 25", was rolled through hand rounds to 2" diameter. Cracking occurred in the early passes and further cropping left too little stock for further rolling. Upon cropping the remaining ingots of the group and removal of surface imperfections (the transverse and longitudinal cracks illustrated in Figures 39-42 of the second quarterly report), insufficient stock remained to warrant rolling.

The five ingots (Table 2) cast since the last quarterly report have all been extruded. The 7-1/2" diameter ingot containing 0.09% zirconium (1207) was extruded at Babcock and Wilcox Tube Company by the Sejournet process described in the last report. The resulting 4-1/4" diameter bar has been cropped and machined for rolling.

The 4" diameter, 30-pound castings were quartered longitudinally and machined to extrusion blanks 1-1/4" diameter x 3" long. These were extruded on a full eccentric, 750-ton press designed for valve extrusion, at Thompson Products Company, Tapco Division. Glass lubrication was used on both billet and die--a fiberglass blanket 1/4" x 3-1/4" x 10" for the billet, and for the die a disk of plate glass 1/8" thick x 1-1/4" diameter with two wads of fiberglass cemented to each side with sodium silicate. The blanks were heated in a Globar furnace in argon atmosphere; the top temperature of the heating zone was 2650 F. Sound stock, 0.805" in diameter, was obtained from the four alloys. The poorest appearing extrusion was the 1.43% aluminum, which exhibited some transverse cracks.

The extruded bars were rolled to 1/2" diameter at the University of Michigan on a slow-speed, two-high rolling mill with square, oval, and round passes. The distance between the rolls could be varied, and rolling was more like hand-round rather than guide-mill rolling. A gas-fired furnace was used for heating the work to 2450 F. Only the aluminum alloy cracked.

Recrystallization

The recrystallization temperature of sound, hot-cold worked bar stock has been determined for the five alloys of the flow sheets, Figures 20-24. The hardness versus annealing temperature of these five alloys is plotted in Figure 25. A 1" diameter bar of unalloyed molybdenum (1159) is included as a datum plane for the 1" diameter stock.

In both 5/8" and 1" diameter, the 0.074% cobalt alloy had the lowest recrystallization temperature of the entire group, including the unalloyed molybdenum. In the fully recrystallized condition this alloy was not so hard

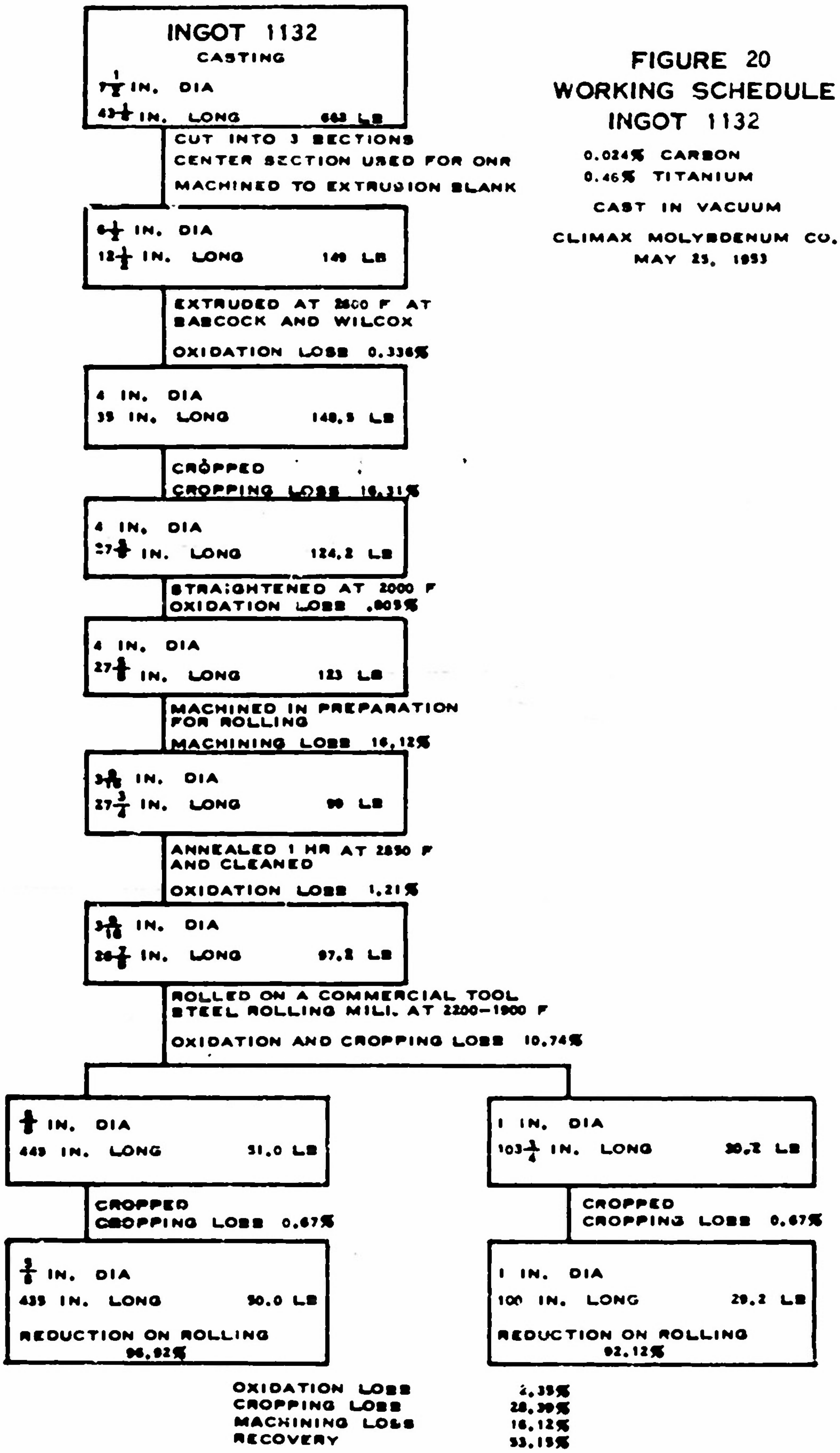
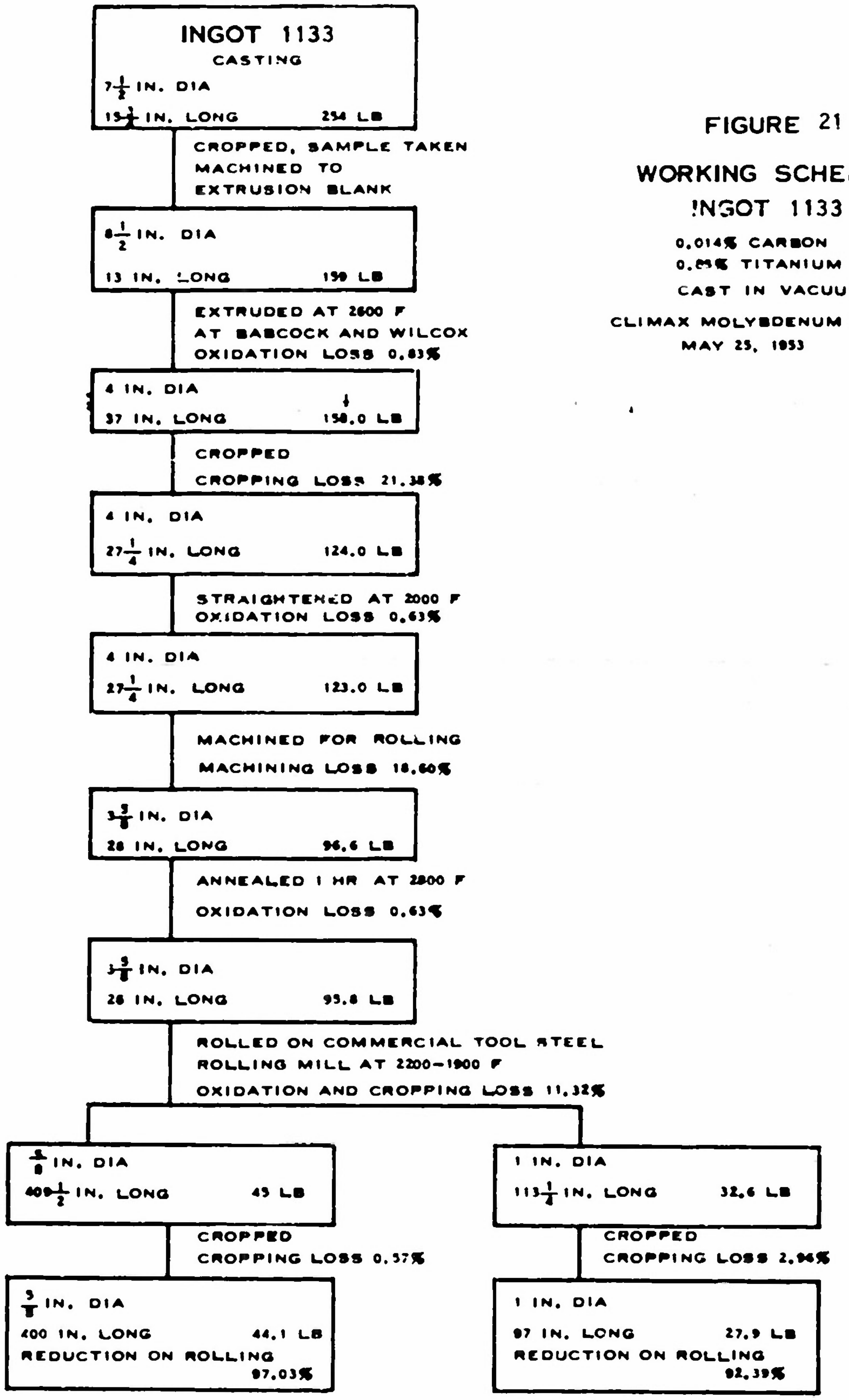


FIGURE 20
WORKING SCHEDULE
INGOT 1132

0.024% CARBON
0.46% TITANIUM

CAST IN VACUUM

CLIMAX MOLYBDENUM CO. 320
MAY 25, 1953



OXIDATION LOSS	1.89%
CROPPING LOSS	36.23%
MACHINING LOSS	16.60%
RECOVERY	45.28%

FIGURE 21

WORKING SCHEDULE

INGOT 1133

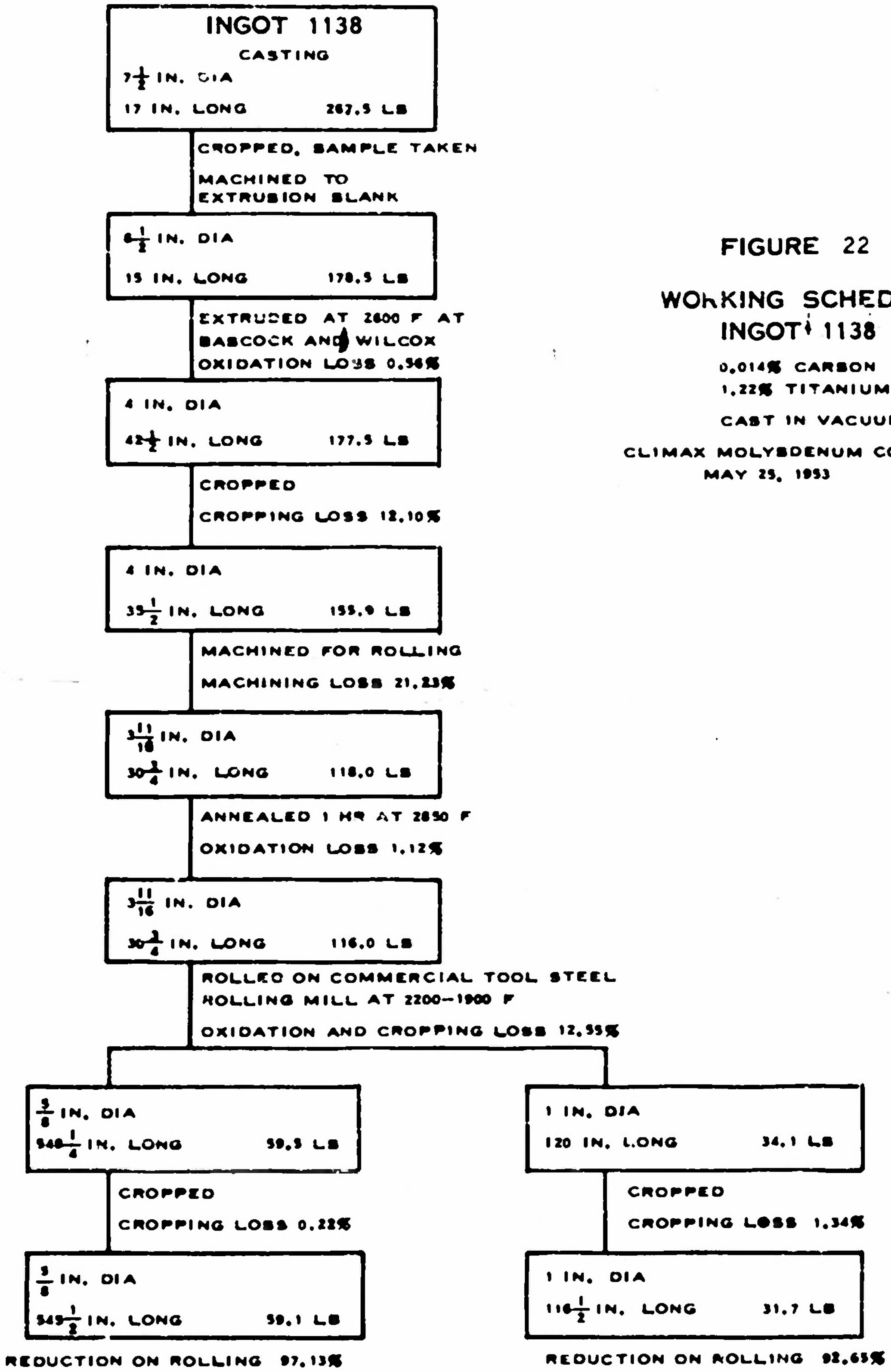
0.014% CARBON

0.05% TITANIUM

CAST IN VACUUM

CLIMAX MOLYBDENUM CO. 321

MAY 25, 1953



OXIDATION LOSS	1.68%
CROPPING LOSS	28.71%
MACHINING LOSS	21.23%
RECOVERY	50.87%

FIGURE 22

WORKING SCHEDULE
INGOT 1138

0.014% CARBON
1.22% TITANIUM

CAST IN VACUUM

CLIMAX MOLYBDENUM CO. 322
MAY 25, 1953

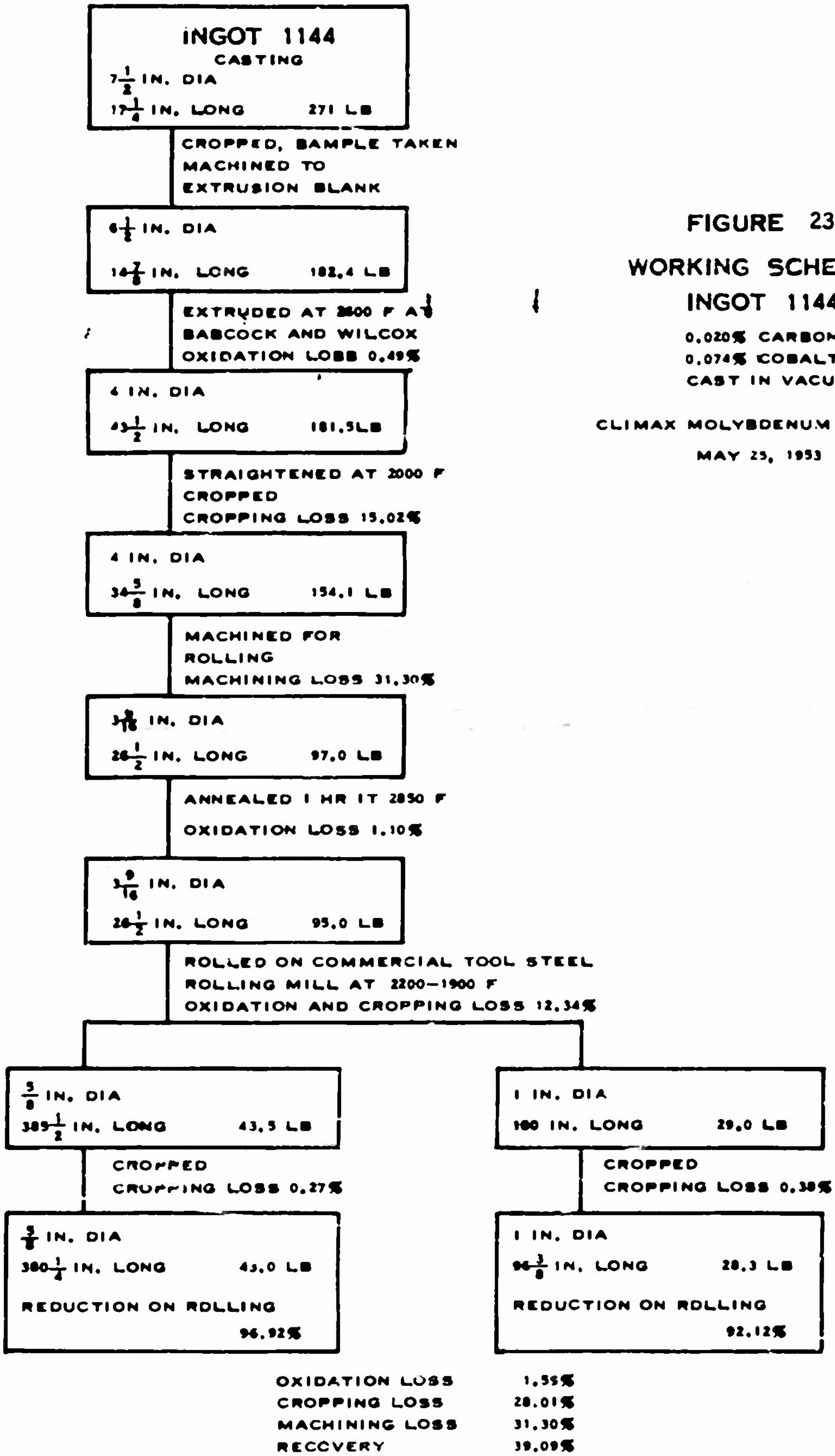


FIGURE 23

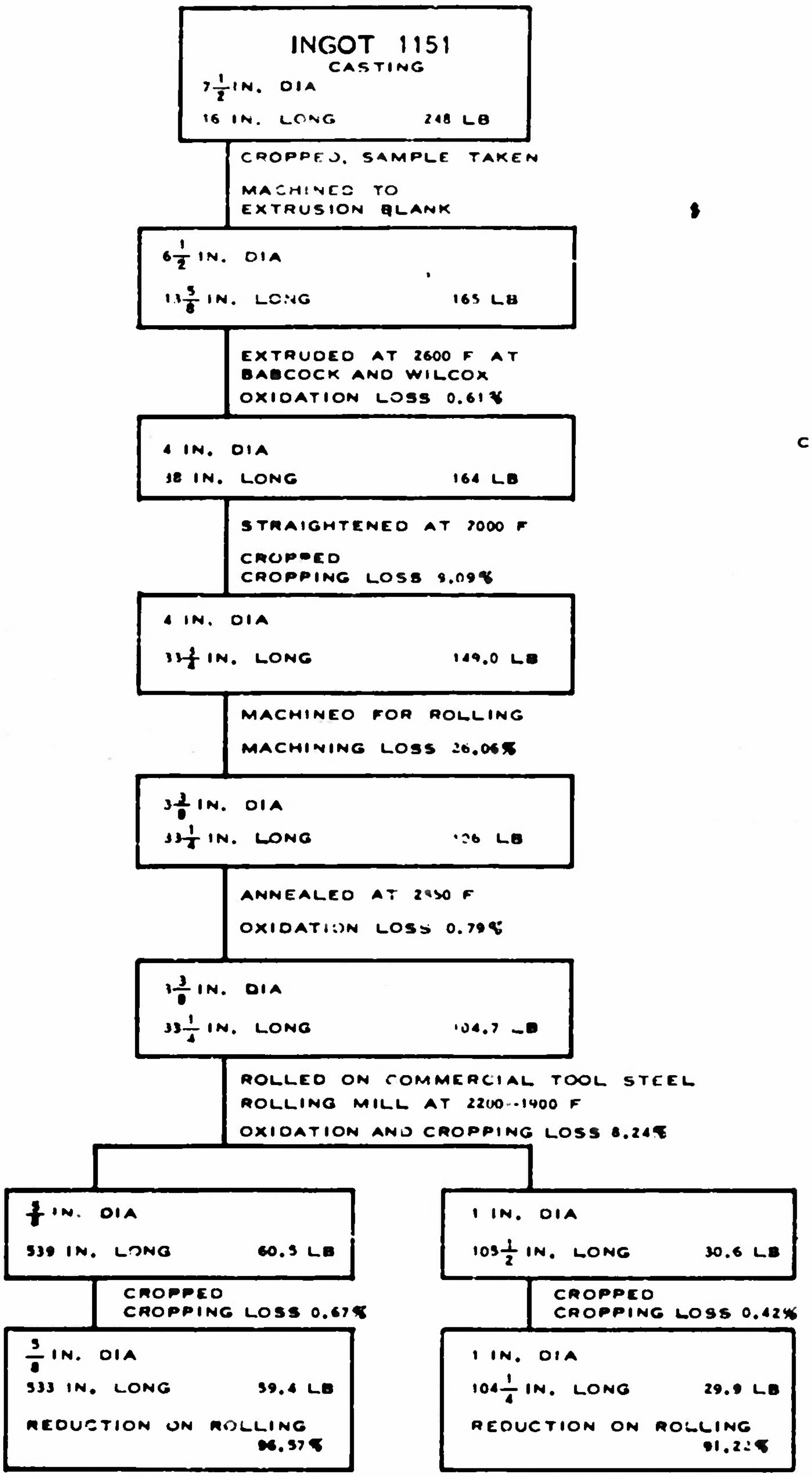
WORKING SCHEDULE

INGOT 1144

0.020% CARBON
0.074% COBALT
CAST IN VACUUM

CLIMAX MOLYBDENUM CO. 323

MAY 25, 1953



OXIDATION LOSS	1.40%
CROPPING LOSS	18.42%
MACHINING LOSS	26.06%
RECOVERY	54.12%

FIGURE 24

WORKING SCHEDULE

INGOT 1151

0.006% CARBON
1.25% VANADIUM

CLIMAX MOLYBDENUM CO. 324
MAY 25, 1953

as carbon-vacuum molybdenum or other molybdenum-base alloys. The highest recrystallization temperatures, on the other hand, were exhibited by the titanium-bearing alloys. The amount of alloy addition was not significant; raising the titanium content from 0.46% to 0.85% and 1.22% did not materially change the recrystallization temperature in either size. The recrystallization temperature of the 1.22% titanium alloy (1138), however, in the 5/8" round, was appreciably lower than that of the 1.26% titanium alloy (1009) of the last quarterly report. There are two possible explanations of the difference: (1) The 1.26% titanium alloy received less hot-cold work than the 1.22% titanium alloy, the former being rolled from 2-3/8" diameter, the latter from 3-3/4" diameter. (2) The actual amount of hot-cold working was not closely controlled, and the number of intermediate heatings may have varied considerably.

The 1.25% vanadium alloy (1151) had essentially the same recrystallization temperature in the 5/8" round as the 1% vanadium alloy of the previous quarterly report.

Hot Hardness of Wrought Alloys

Vickers hardness has been determined from room temperature to 1600 F on rolled bars 5/8" and 1" in diameter, in three structural conditions, e.g., as rolled, stress relieved, and fully recrystallized. The hardnesses of the alloys rolled during the past quarter are plotted in Figures 26-40.

The hot hardnesses of carbon-vacuum, unalloyed molybdenum bars (937 and 1159), which have been carried through all phases of this investigation as a datum plane of reference, are given in Figures 26-27. Bar 1045, Figure 28, was also unalloyed molybdenum, but differed from Bars 937 and 1159 in that it was deoxidized with rare earth metals. The hot hardness of this bar was not significantly different from that of Bar 937 in any of the structural conditions studied.

The hot hardnesses of molybdenum containing 0.17, 0.49, and 0.53% aluminum are presented in Figures 29-31. In a previous discussion of cast alloys (second quarterly report), it was reported that the hardness did not drop so rapidly with increase in temperature for the aluminum-molybdenum alloys as it did for unalloyed molybdenum or molybdenum containing niobium, titanium, or vanadium in the concentrations under investigation at that time. Comparison of Figures 29-31 with Figures 26-27 indicates that the same situation existed in the wrought alloys. The 0.17% aluminum bar (1063) was somewhat lower in hardness at 1600 F than the unalloyed Bar 937 in each condition studied, but the alloys with a greater amount of aluminum (1058, 987) were considerably harder at 1600 F than unalloyed molybdenum.

Figures 32-34 are hot hardness curves of wrought molybdenum containing 0.24, 0.52, and 0.75% niobium, respectively. In the as-rolled ans stress-relieved conditions, 5/8" diameter bars of these alloys were significantly harder than comparable unalloyed molybdenum. The increase was noticeably less, however, after recrystallization. In contrast to other alloy systems under investigation, in the molybdenum-niobium system the factor of bar size was of considerable significance.

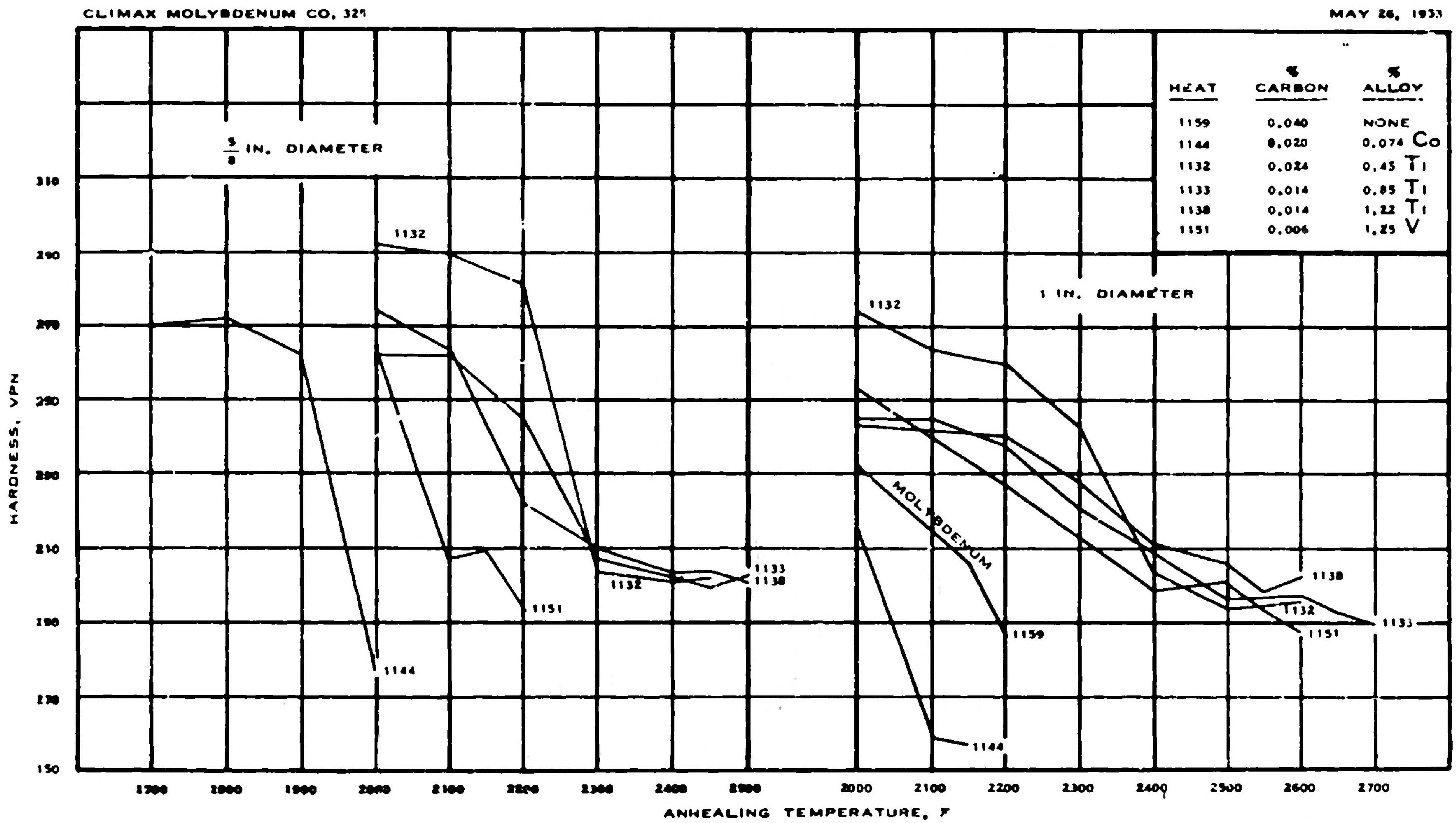


FIGURE 25 – RECRYSTALLIZATION OF BAR STOCK OF INDICATED COMPOSITIONS

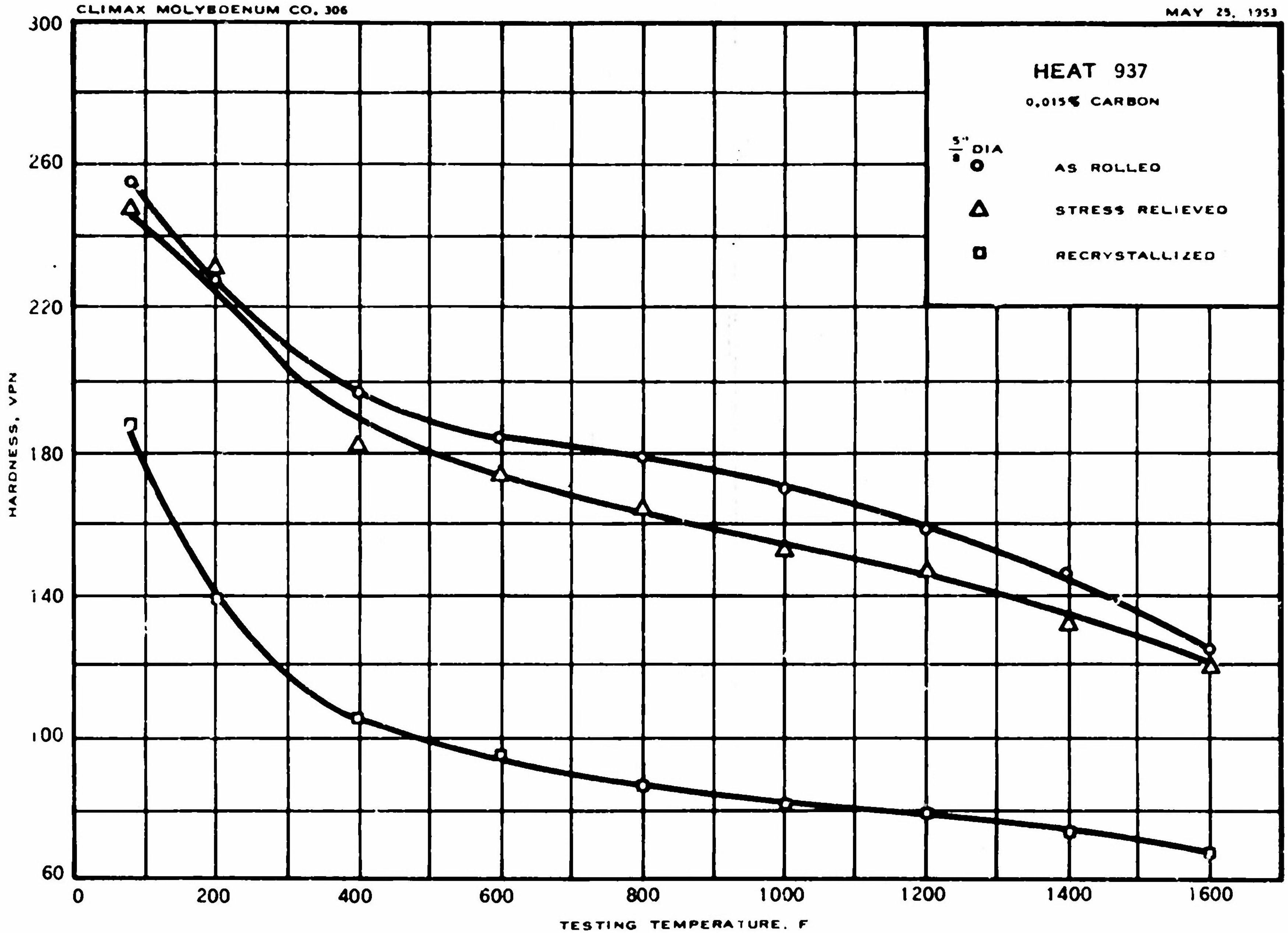


FIGURE 26 – HOT HARDNESS OF ROLLED BARS OF UNALLOYED MOLYBDENUM

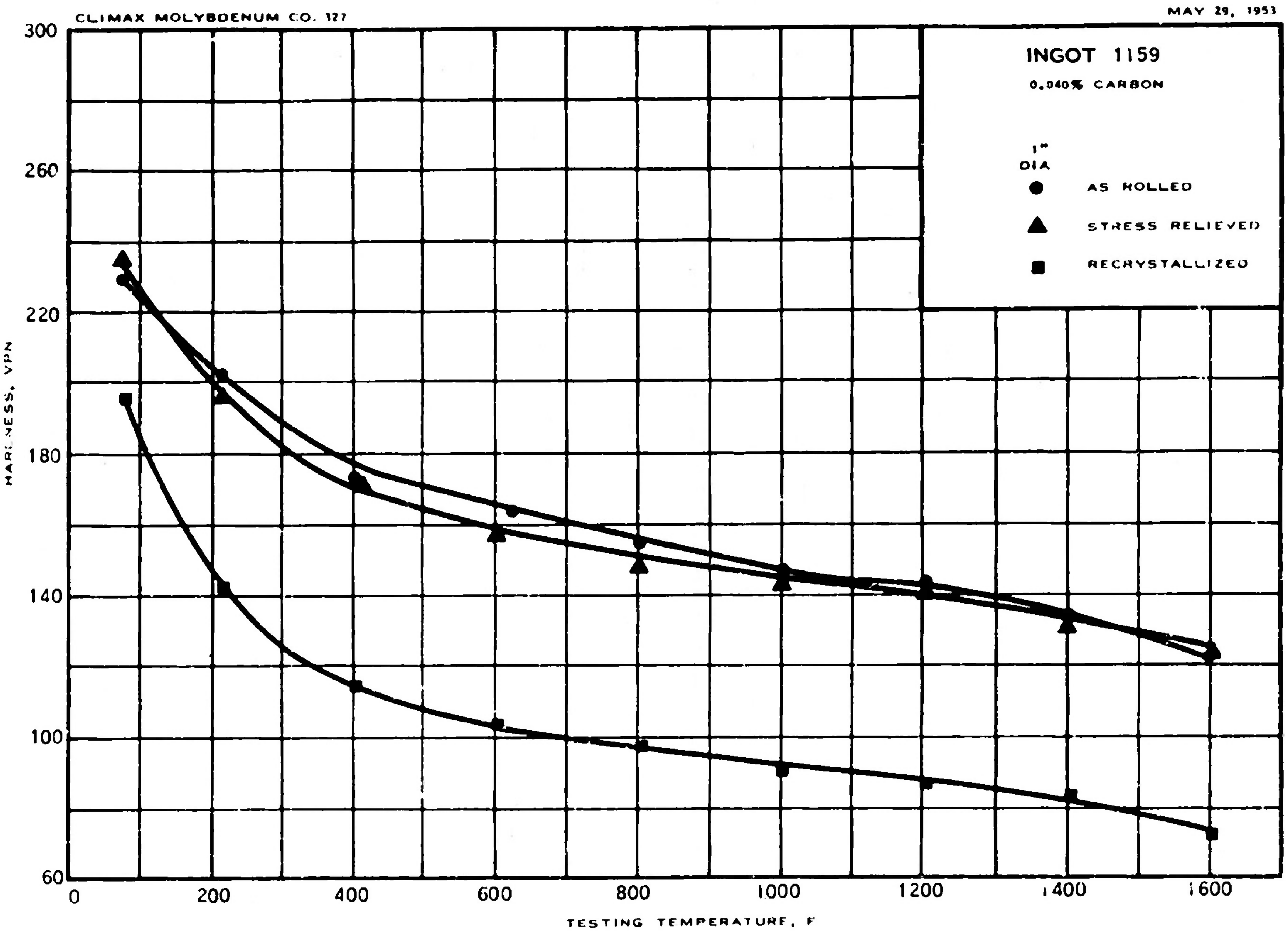


FIGURE 27 – HOT HARDNESS OF ROLLED BARS OF UNALLOYED MOLYBDENUM

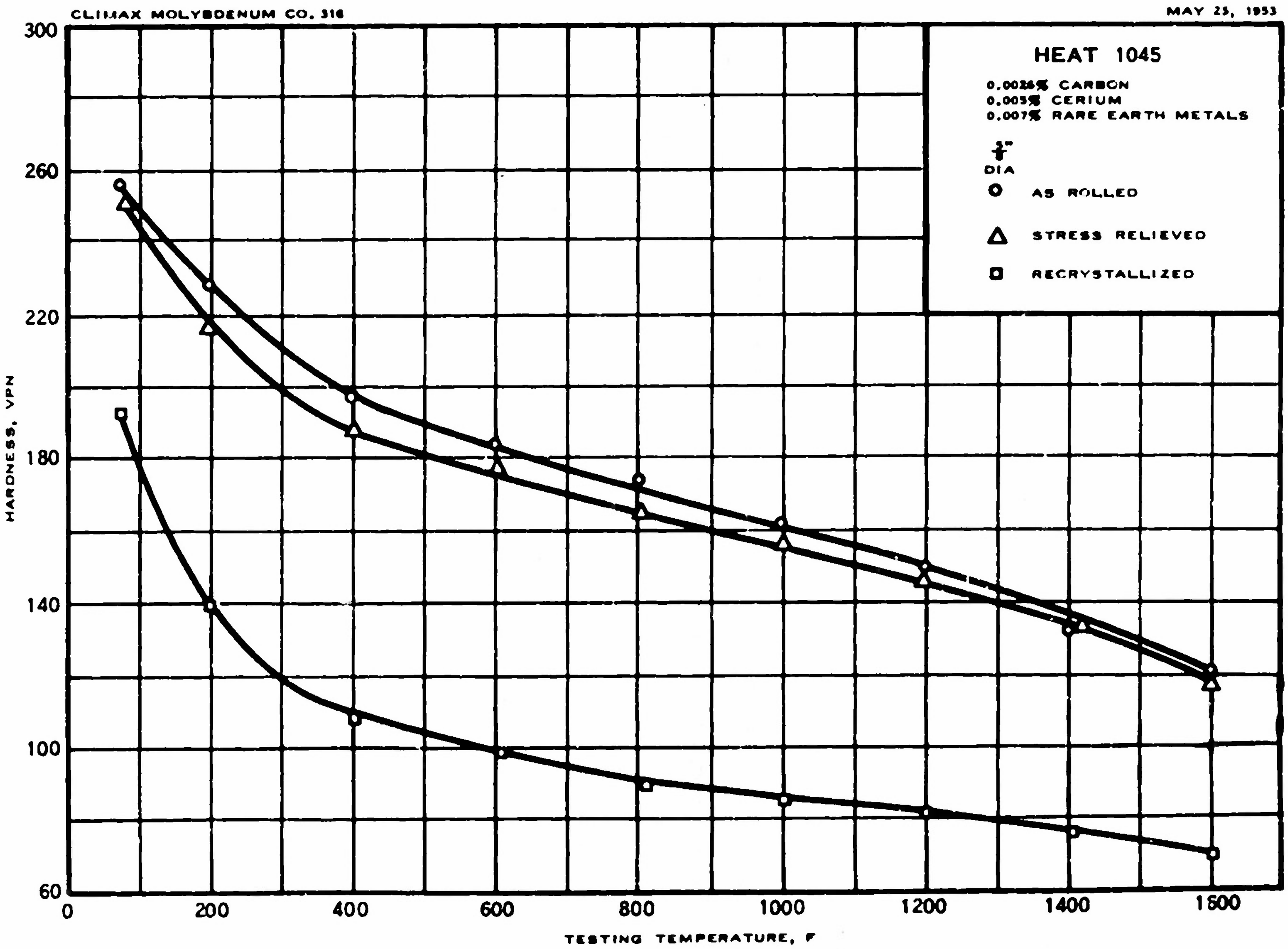


FIGURE 28 — HOT HARDNESS OF ROLLED BARS OF MOLYBDENUM DEOXIDIZED WITH RARE EARTH METALS

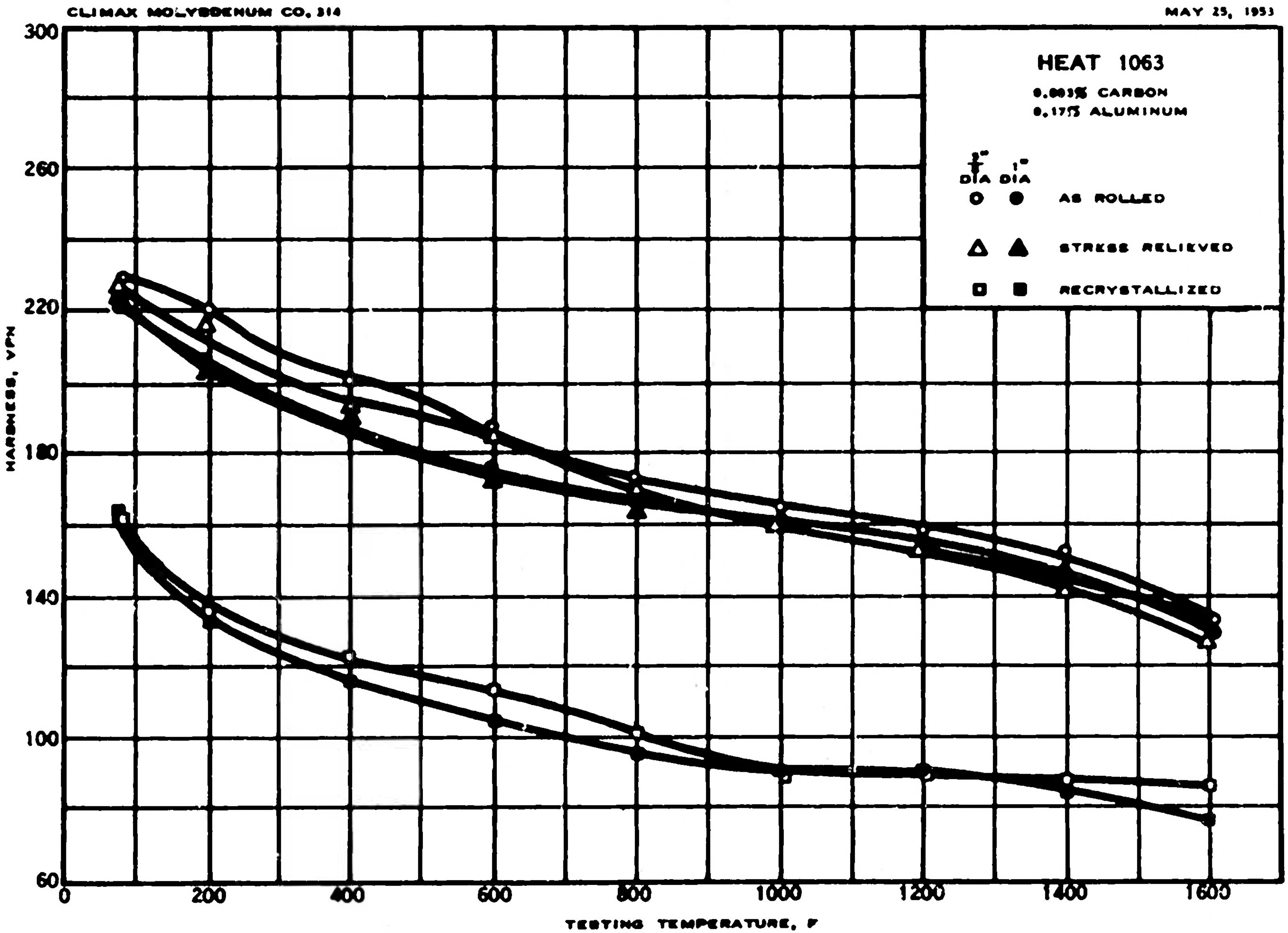


FIGURE 29 – HOT HARDNESS OF ROLLED BARS OF 0.17% ALUMINUM–MOLYBDENUM ALLOY

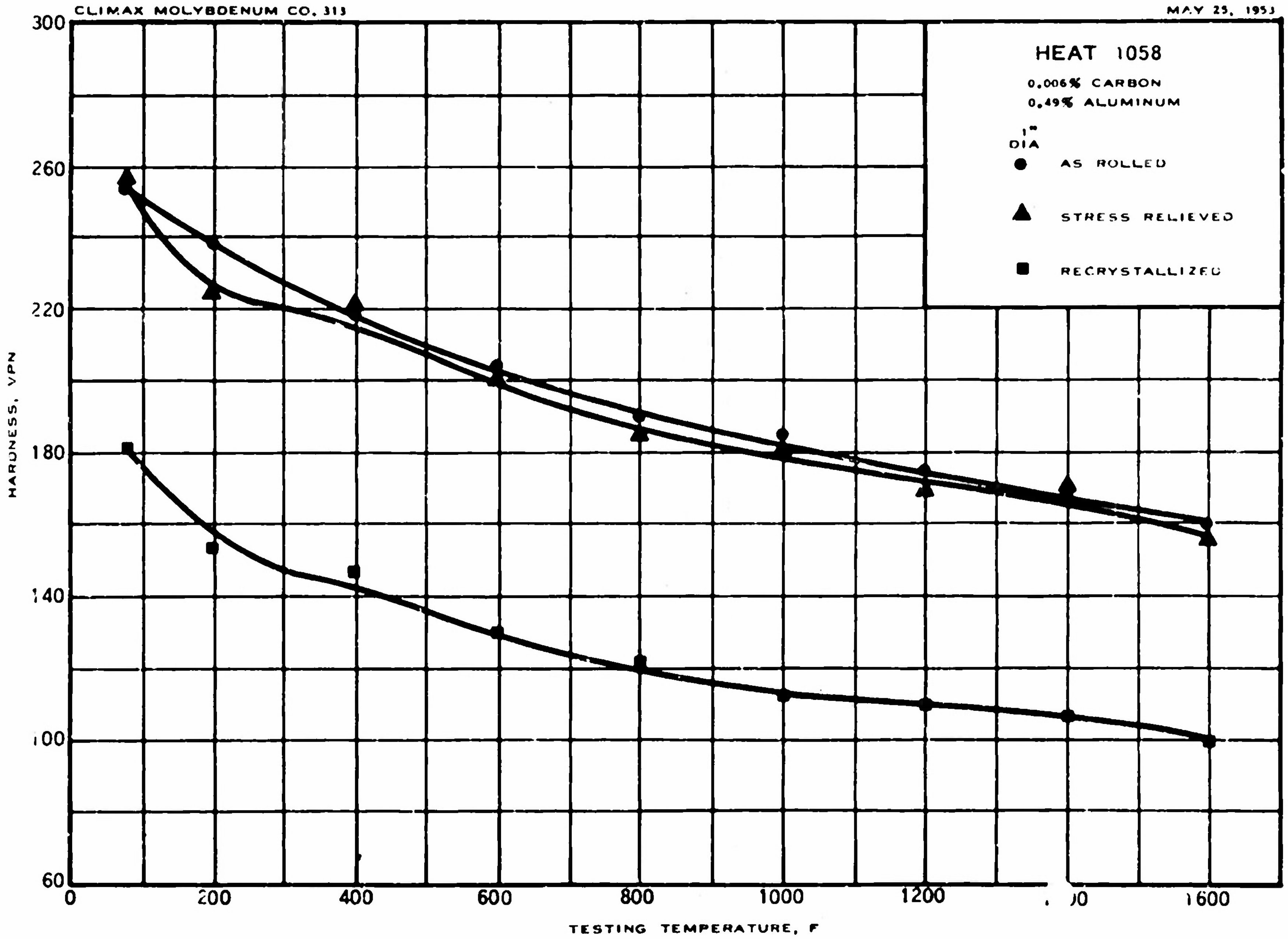


FIGURE 30 – HOT HARDNESS OF ROLLED BARS OF 0.49% ALUMINUM–MOLYBDENUM ALLOY

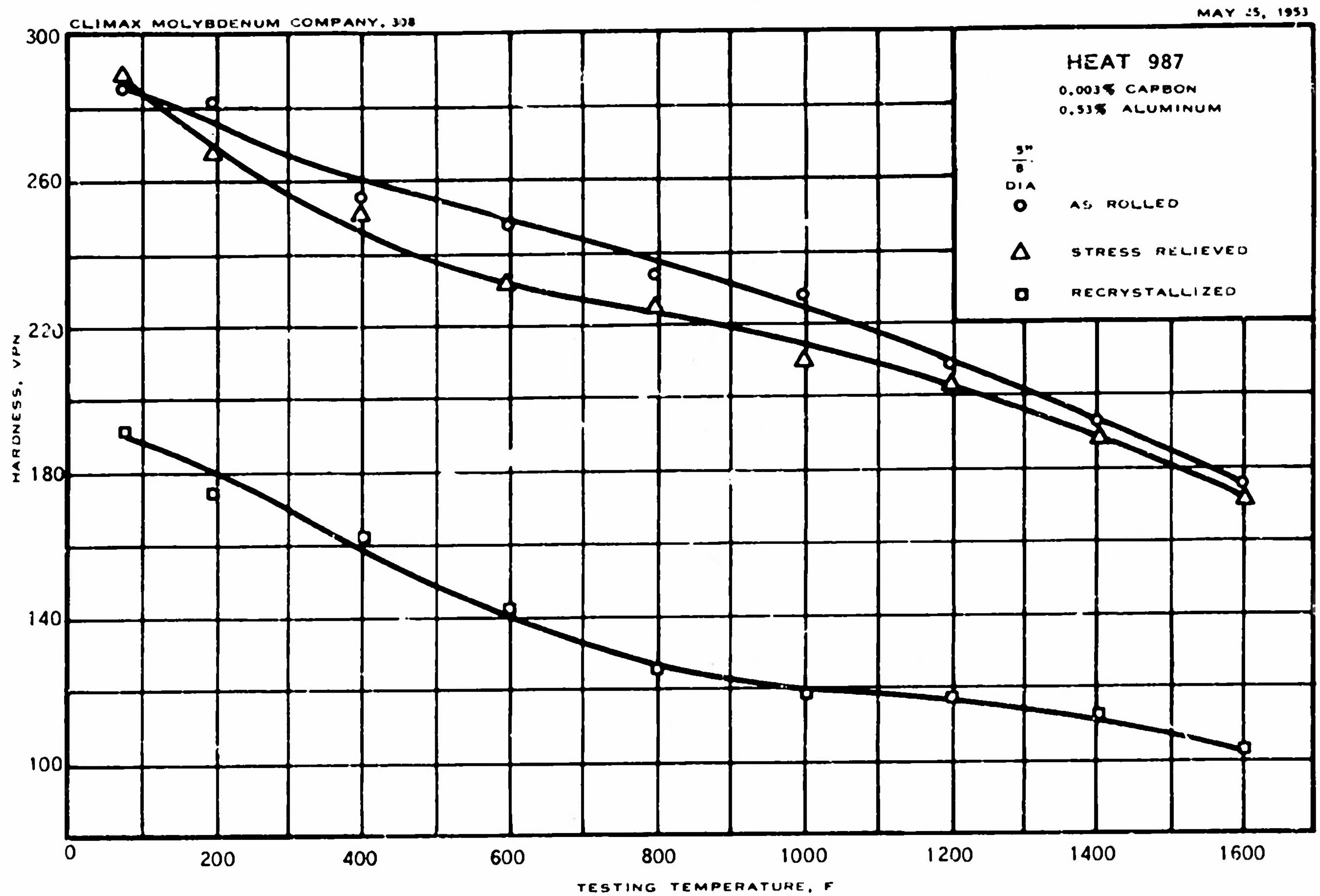


FIGURE 31 – HOT HARDNESS OF ROLLED BARS OF 0.53% ALUMINUM–MOLYBDENUM ALLOY

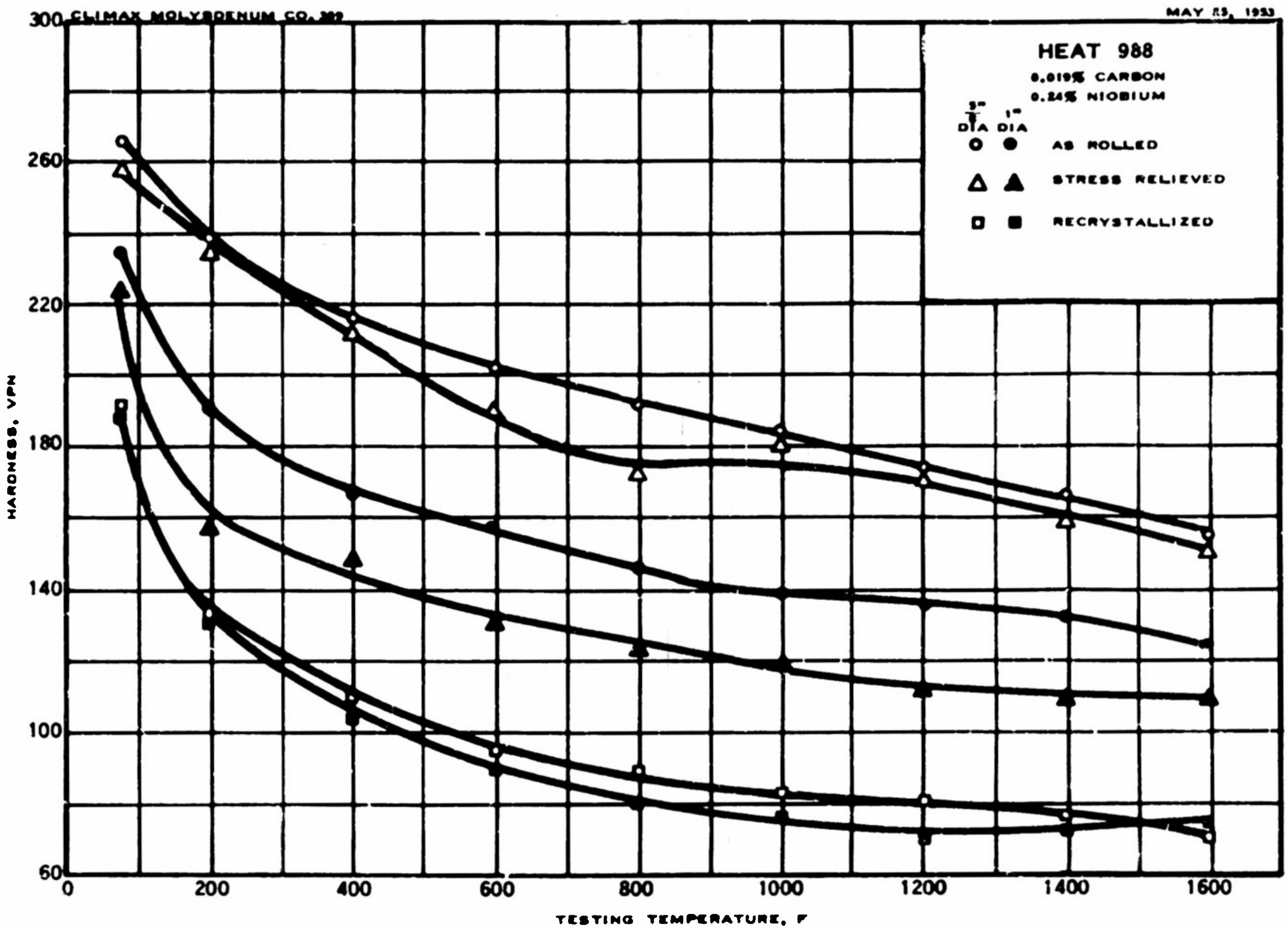


FIGURE 32 – HOT HARDNESS OF ROLLED BARS OF 0.24% NIOBIUM–MOLYBDENUM ALLOY

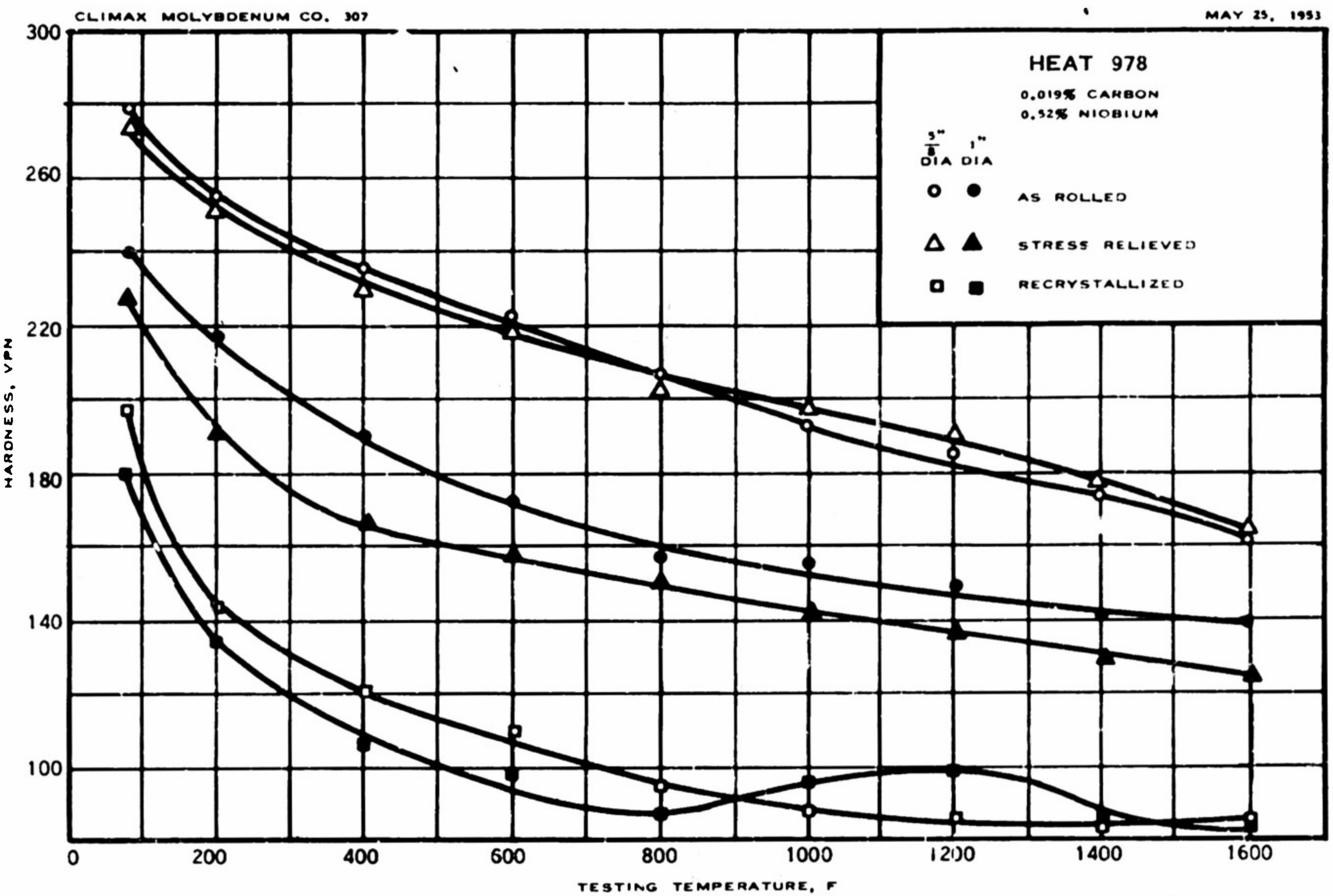


FIGURE 33 - HOT HARDNESS OF ROLLED BARS OF 0.52% NIOBIUM-MOLYBDENUM ALLOY

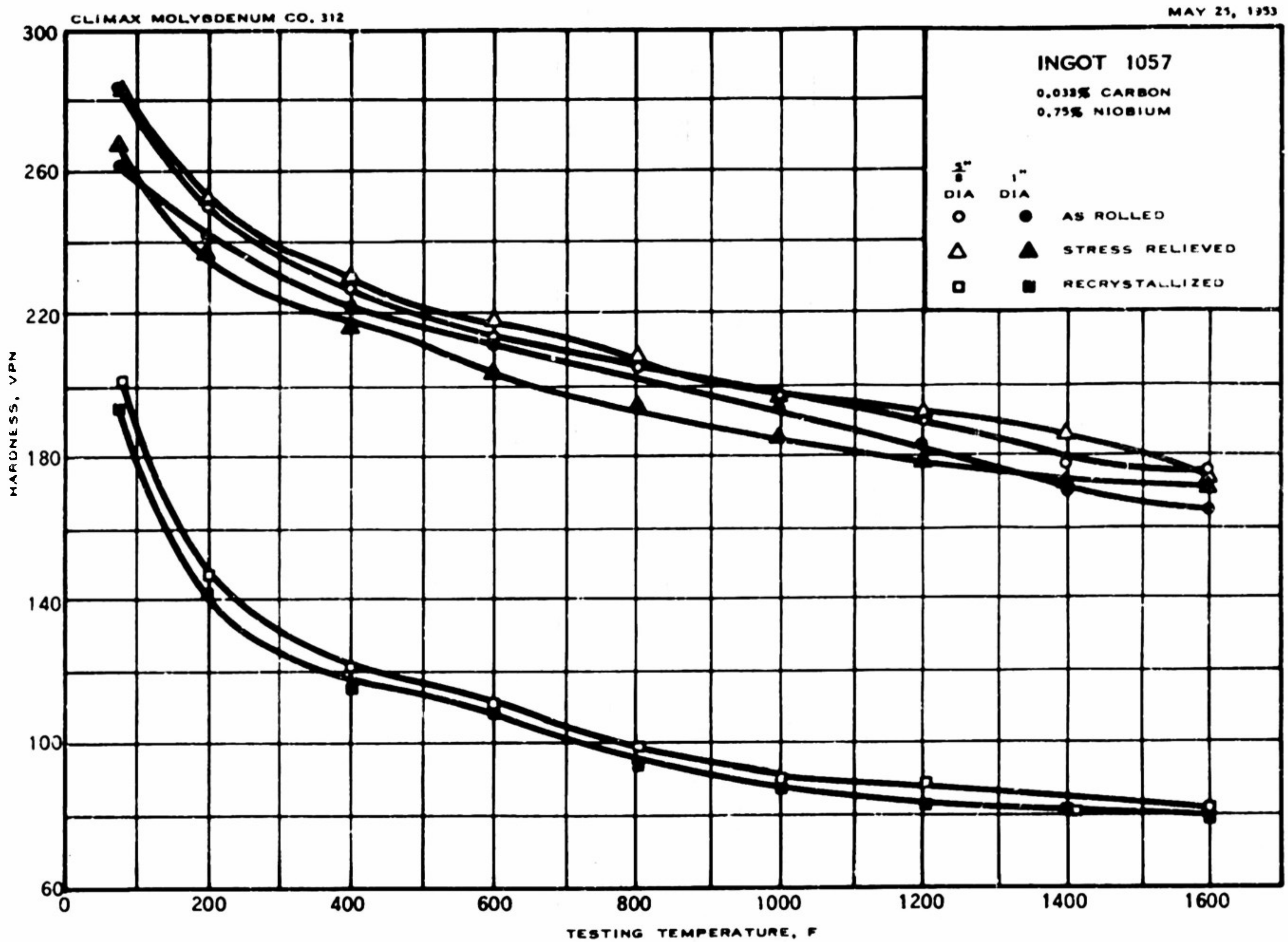


FIGURE 34 – HOT HARDNESS OF ROLLED BARS OF 0.75% NIOBIUM–MOLYBDENUM ALLOY

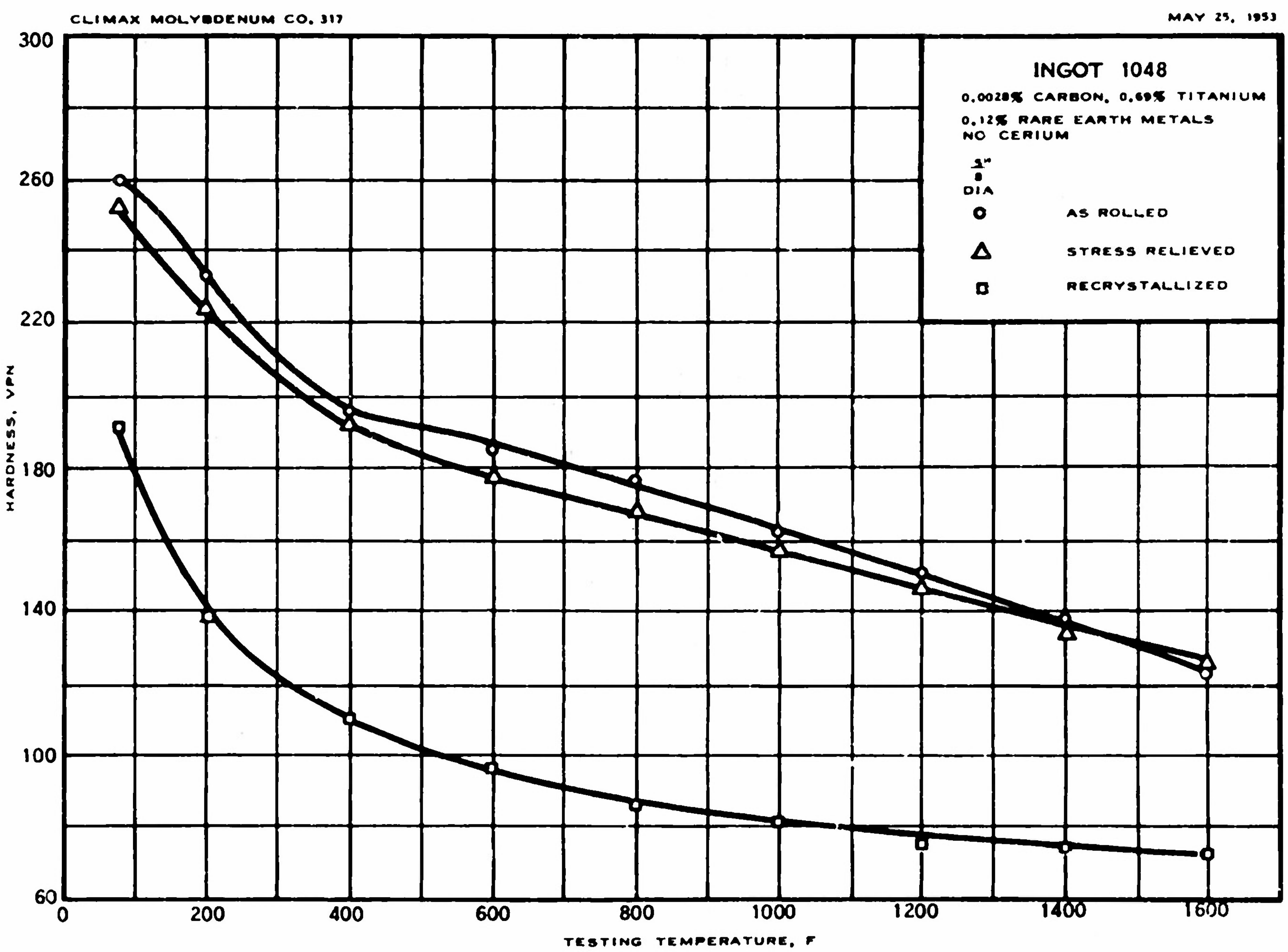


FIGURE 35 – HOT HARDNESS OF ROLLED BARS OF 0.69% TITANIUM–MOLYBDENUM ALLOY DEOXIDIZED WITH RARE EARTH METALS

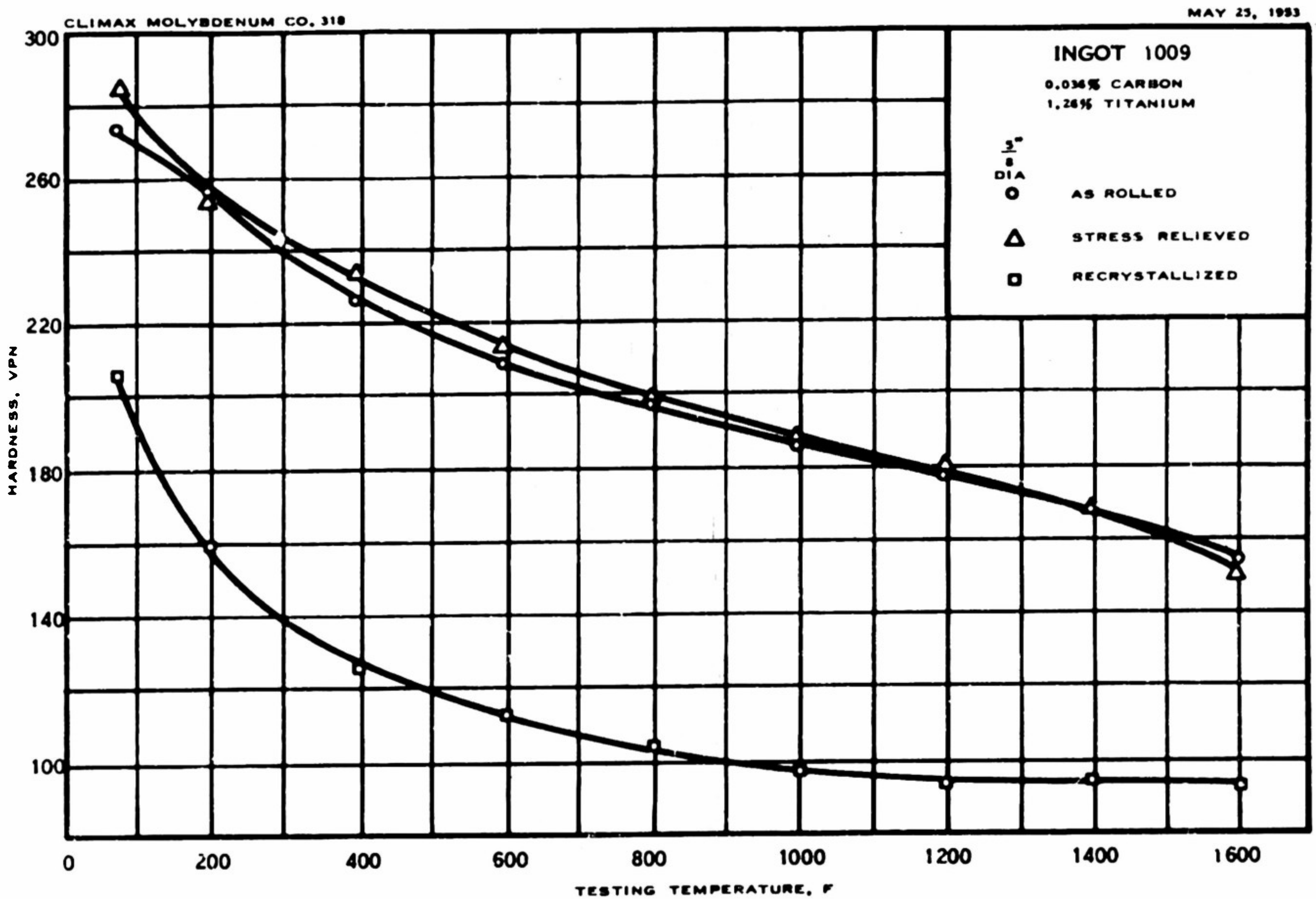


FIGURE 36 – HOT HARDNESS OF ROLLED BARS OF 1.26% TITANIUM–MOLYBDENUM ALLOY

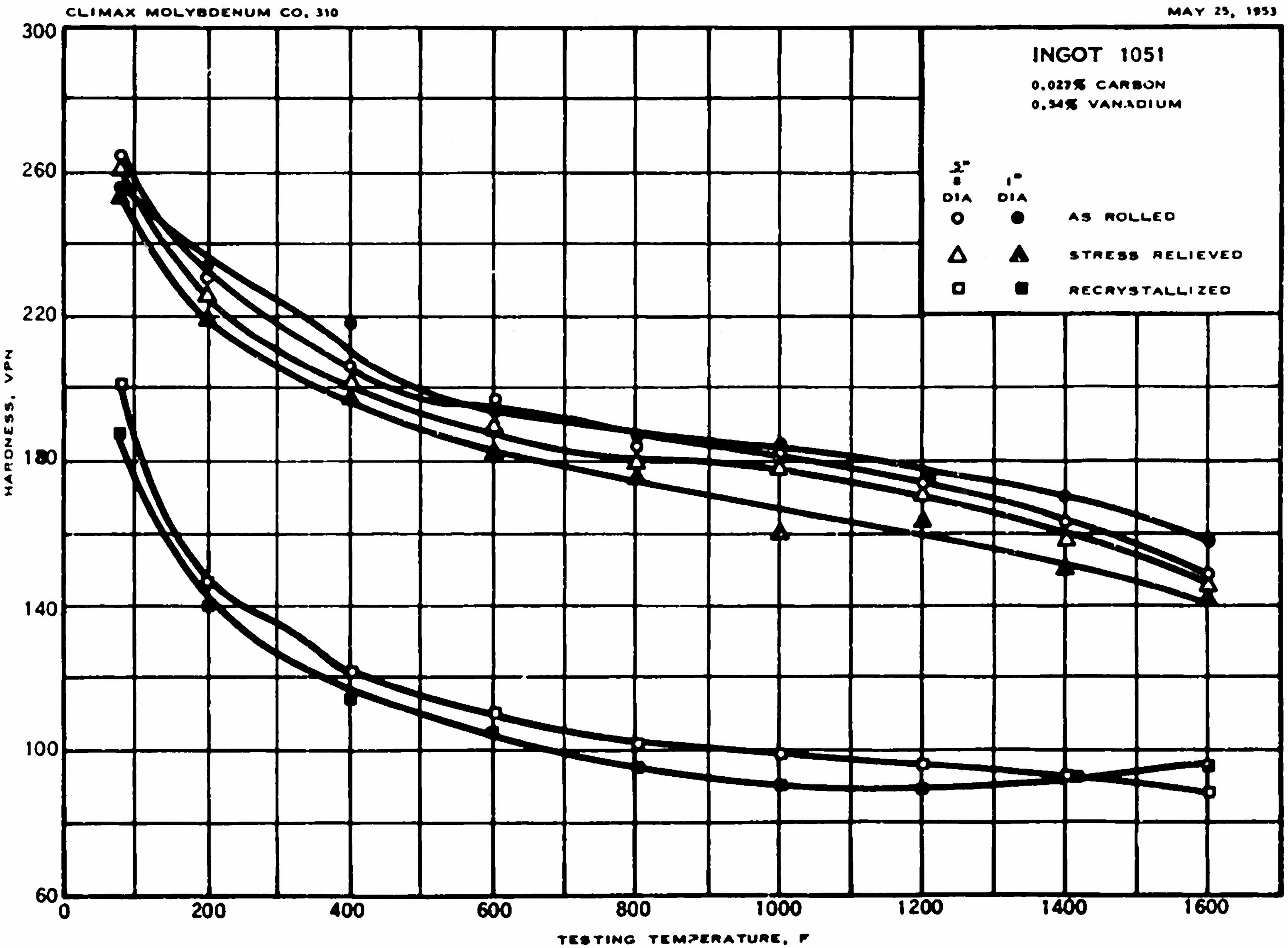


FIGURE 37 – HOT HARDNESS OF ROLLED BARS OF 0.54% VANADIUM–MOLYBDENUM ALLOY

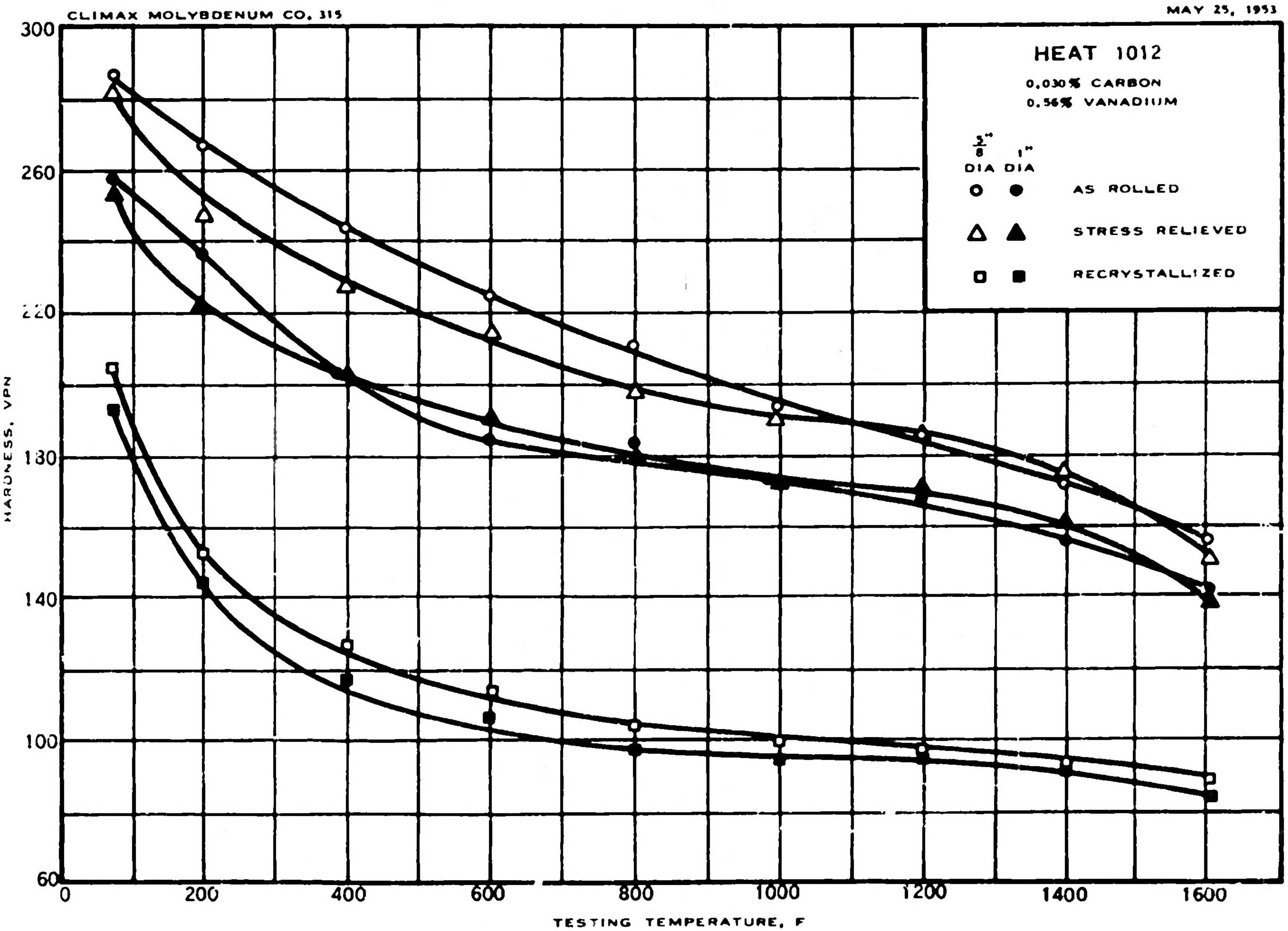


FIGURE 38 – HOT HARDNESS OF ROLLED BARS OF 0.56% VANADIUM-MOLYBDENUM ALLOY

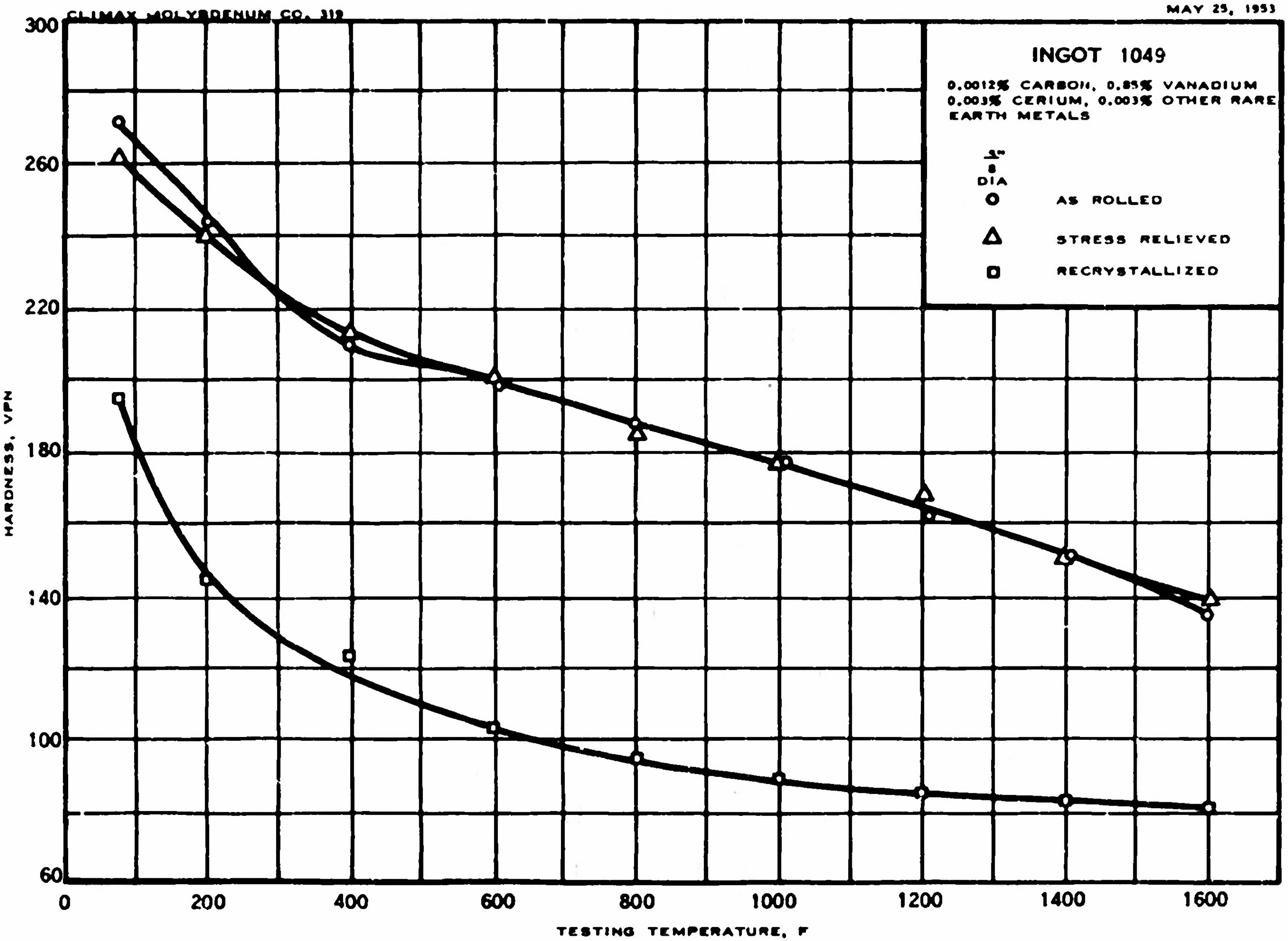


FIGURE 39 — HOT HARDNESS OF ROLLED BARS OF 0.85% VANADIUM—MOLYBDENUM ALLOY DEOXIDIZED WITH RARE EARTH METALS

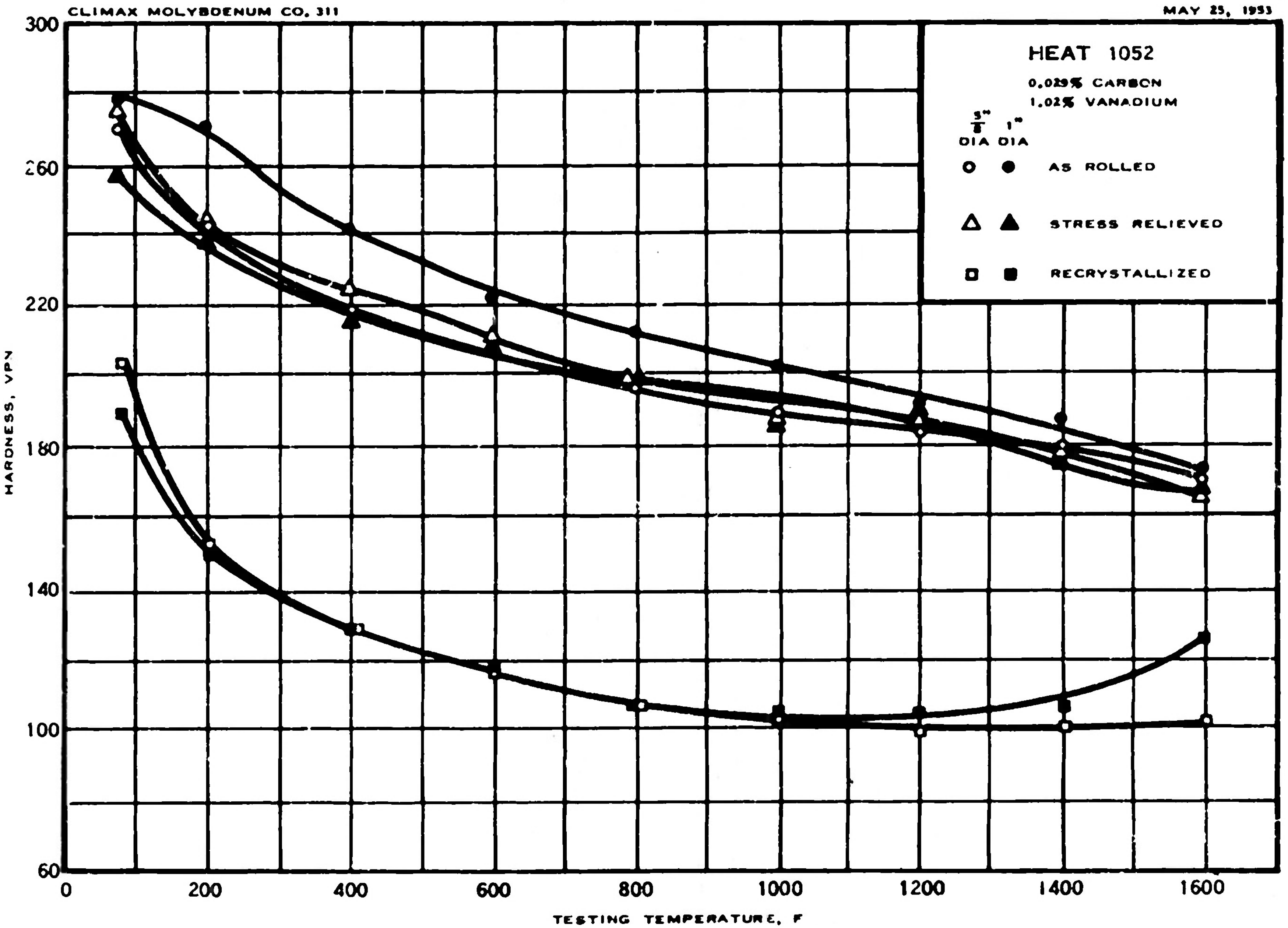


FIGURE 40 — HOT HARDNESS OF ROLLED BARS OF 1.02% VANADIUM—MOLYBDENUM ALLOY

The 0.69% titanium alloy deoxidized with rare earth metals, Figure 35, was not superior in hot hardness to unalloyed molybdenum deoxidized with carbon or rare earth metals, regardless of condition or testing temperature. Increase in titanium content to 1.26%, Figure 36, raised the hardness of the alloy in all structural conditions.

The data available on the molybdenum-vanadium system are presented in Figures 37-40. The hardnesses of the three alloys of low vanadium content were about the same at 1600 F, and the 1% vanadium alloy, Figure 40, was markedly harder in all structural conditions. As in the case of the alloys as cast, the 0.85% vanadium alloy deoxidized with rare earth metals did not have the hot hardness anticipated on the basis of interpolation from the hot hardness of molybdenum containing various amounts of vanadium.

Tensile Properties

Tensile tests have been performed upon 5/8" and 1" diameter bars at room temperature, 750, 1200, and 1600 F, in three structural conditions: as rolled, stress relieved and fully recrystallized. For all tests the strain rate was 3% per hour in the elastic range and 60% per hour in the plastic range. The results of the tests are given in Table 3. In general, the 5/8" diameter bar stock exhibited higher tensile strengths than the 1" diameter stock of the same material. This greater strength was notable in the as-rolled and the stress-relieved alloys and was almost insignificant in the fully recrystallized alloys. This was expected, because of the greater amount of hot-cold work on the 5/8" diameter stock. In the recrystallized alloys the factor of hot-cold work was removed and the tensile strengths of the 5/8" and 1" diameter bars were therefore much the same.

As a general rule, the 5/8" diameter bars were more ductile than the 1" diameter bars.

It was noted in the previous quarterly report that bars deoxidized with aluminum or rare earth metals were less ductile at room temperature after recrystallization heat treatment than before. This phenomenon was observed in the following molybdenum-base materials: 0.85% vanadium, 0.69% titanium, unalloyed molybdenum--each deoxidized with rare earth metals--and 0.53% aluminum. This loss of ductility was not manifested, however, by the 0.17% aluminum and 0.49% aluminum alloys of the present series. Moreover, high ductility in the tensile test at 750 F was exhibited by the recrystallized bars that had been brittle at room temperature. This suggests that the transition temperature had shifted to a value close to room temperature. Tests are now under way to determine transition temperatures under conditions of the tensile test for several of the bars exhibiting both brittle and ductile failure at room temperature. To date, the transition temperature of recrystallized samples of unalloyed molybdenum (937) has been established at between 14 and 18 F.

A summary of the relative tensile strengths at room temperature and 1600 F of the alloys under study is presented in Figure 41.

Considering first the alloys containing aluminum, it appears that aluminum exerts more effect upon the strength of molybdenum at 1600 F than at room temperature. The 0.17% aluminum alloy was approximately equivalent in strength to the unalloyed bar (937). The 0.49% and 0.53% aluminum alloys were very low in room temperature strength in the recrystallized condition, which parallels the low room-temperature ductility of the molybdenum-aluminum alloys after recrystallization.

TABLE 3

TENSILE PROPERTIES AT ROOM AND ELEVATED TEMPERATURES OF ROLLED MOLYBDENUM-BASE ALLOYS

Bar Dia In.	(1) Condition	Testing Temp,F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
		Bar 937 - Unalloyed Mo				
5/8	as rolled	81	78,800*	102,200	40	61.1
		750	53,400*	79,300	20	82.4
		1200	49,800*	69,600	18	84.2
		1600	37,000*	52,000	24	88.6
	str. relieved	81	82,900*	97,200	42	69.0
		750	57,200*	62,400	20	81.2
		1200	48,100*	65,200	22	86.1
		1600	33,400*	52,400	24	88.6
	recrystallized (2150 F)	81	55,900	68,200	42	37.8
		750	21,000	39,200	60	84.7
		1200	11,000	33,600	57	84.8
		1600	7,600*	25,100	60	84.6
	Bar 1045 - Unalloyed Mo Deoxidized with Rare Earth Metals					
5/8	as rolled	78	83,300*	105,300	25	34.5
		1600	45,800*	55,000	11	47.8
	str. relieved	78	81,500*	100,900	9	13.8
		1600	43,400*	55,000	19	76.9
	recrystallized (2400 F)	78	46,600	62,500	2	12.3
		1600	11,300*	25,600	55	86.4
		Bar 1063 - 0.17% Aluminum				
5/8	as rolled	78	75,200*	96,300	36	57.1
		750	59,400*	76,400	19	70.6
		1200	56,100*	68,900	16	77.1
		1600	40,700	58,700	20	76.1
	str. relieved	78	72,400*	94,700	40	63.1
		750	54,600*	74,100	24	74.7
		1200	54,900*	66,400	18	71.3
		1600	45,200*	60,600	18	74.1
	recrystallized (2200 F)	78	41,300	66,700	18	14.4
		750	21,900	43,500	58	81.1
		1200	15,800	39,800	50	79.8
		1600	10,800	29,100	49	80.9

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature

(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars

* 0.1% offset yield strength taken from stress-strain plot; all other yield strength values from drop in load

TABLE 3 (continued)

Bar Dia In.	(1) Condition	Testing Temp, F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
			Bar 1063 - 0.17% Aluminum (continued)			
1	as rolled	78	-	74,900	2	2.8
		750	53,600*	61,400	20	75.1
		1200	-	55,600	17.5	76.1
		1600	39,400*	47,200	21.5	81.0
	str. relieved	78	64,500	74,600	1.5	1.1
		750	-	58,900	20.5	76.8
		1200	-	55,200	19	75.0
		1600	-	48,200	18.5	79.3
	recrystallized (2250 F)	79	34,200	65,200	21.5	18.8
		780	10,700	39,300	56	80.3
		1200	10,300	36,900	46.5	79.4
		1600	12,500	25,900	56.5	88.7
			Bar 987 - 0.53% Aluminum			
5/8	as rolled	78	102,000*	121,200	2	0.2
		750	79,600*	101,900	14.5	57.5
		1200	74,700*	91,400	16	66.9
		1600	55,400*	76,800	18	63.7
	str. relieved	78	98,200	105,800	3	2.0
		750	79,000*	88,400	19	60.4
		1200	66,600*	82,900	18	82.1
		1600	55,300*	72,100	19	68.6
	recrystallized (2200 F)	78	none	46,100	0	0
		750	43,800	56,200	42	72.3
		1200	37,900	51,400	41	80.0
		1600	17,700*	38,100	42	54.7
			Bar 1058 - 0.49% Aluminum			
1	as rolled	78	82,200*	89,200	1.5	0.6
		750	-	75,700	18.5	71.8
		1200	66,300*	71,700	17	71.9
		1600	55,300	61,500	17.5	76.0
	stress relieved	78	81,300	85,500	1	0.2
		750	67,700	74,100	19	72.3
		1200	65,500	70,800	16.5	69.5
		1600	-	62,300	18.5	78.8

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature

(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars

* 0.1% offset yield strength taken from stress-strain plot; all other yield strength values from drop in load

TABLE 3 (continued)

Bar Dia In.	(1) Condition	Testing Temp, F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
		Bar 1058 - 0.49% Aluminum (continued)				
1	recrystallized (2300 F)	79	45,900	64,000	6	5.6
		750	26,300	42,200	40	73.1
		1200	25,500	46,600	41	81.4
		1600	13,700	34,100	50.5	83.2
		Bar 988 - 0.24 Niobium				
5/8	as rolled	78	91,000*	106,100	28	41.9
		750	62,300*	84,800	19	78.9
		1200	60,000*	78,000	19	82.0
		1600	45,600*	65,900	16	77.7
	str. relieved	78	90,000	103,300	34	63.6
		750	64,000*	83,600	17	71.1
		1200	54,100*	77,300	18	74.5
		1600	58,200*	66,500	20	82.1
	recrystallized (2200 F)	78	68,700	71,300	40	28.7
		750	25,800	39,700	54	86.6
		1200	15,500	36,300	43	76.6
		1600	16,700*	30,100	61	82.7
1	as rolled	78	70,100*	80,600	1	0.6
		750	50,600*	52,100	20	80.0
		1200	48,100*	50,700	19	83.1
		1600	39,700	44,200	19	84.9
	str. relieved	78	62,200	69,300	1	1.7
		750	43,800*	45,600	23	81.4
		1200	40,000*	41,900	21	85.9
		1600	35,300*	37,300	21.5	87.7
	recrystallized (2500 F)	76	40,000	55,200	3	2.5
		750	13,100	33,400	57.5	76.7
		1200	9,300	28,100	49	84.7
		Bar 978 - 0.52% Niobium				
5/8	as rolled	78	92,600*	114,600	28	54.8
		750	71,500*	92,500	18	68.8
		1200	50,900*	80,800	16	78.9
		1600	51,100*	71,300	18	73.9

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature

(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars

* 0.1% offset yield strength taken from stress-strain plot; all other yield strength values from drop in load

TABLE 3 (continued)

Bar Dia In.	(1) Condition	Testing Temp, F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
			Bar 978 - 0.52% Niobium (continued)			
5/8	str. relieved	78	94,300	109,400	29	59.4
		750	68,300*	89,400	17	70.7
		1200	67,200*	82,700	16	72.9
		1600	58,600*	72,700	16	72.3
	recrystallized (2200 F)	78	62,800	71,900	27	21.8
		750	32,100	42,600	60	85.3
		1200	17,500	39,500	48	85.5
		1600	-	34,900	52	88.8
1	as rolled	78	72,200*	83,700	1	1.7
		750	58,400*	59,600	21	83.2
		1200	48,000*	54,400	17.5	79.8
		1600	-	49,400	18.5	80.4
	str. relieved	78	68,000	78,600	1.5	0.5
		750	50,000*	55,100	20.5	81.8
		1200	47,400*	52,400	18	83.1
		1600	40,700	44,200	22	79.8
	recrystallized (2450 F)	80	42,800	65,500	10	8.5
		750	11,100	36,600	47	78.6
		1200	8,900	33,000	50.5	82.7
		1600	9,600*	30,000	40.5	86.9
			Bar 1057 - 0.75% Niobium			
5/8	as rolled	78	94,400*	118,300	32	62.5
		750	74,200*	96,600	17	79.8
		1200	-	89,000	17	77.3
		1600	41,400*	73,100	12	71.1
	str. relieved	78	96,000*	118,100	33	66.7
		750	73,700*	96,000	17	71.2
		1200	67,400*	88,400	16	73.7
		1600	48,700*	76,700	17	67.6
	recrystallized (2250 F)	78	66,400	78,400	53	70.1
		750	27,300	46,300	52	81.2
		1200	18,900	43,600	48	76.5
		1600	13,600	36,000	61	83.6

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature

(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars

* 0.1% offset yield strength taken from stress-strain plot; all other yield strength values from drop in load

TABLE 3 (continued)

Bar Dia In.	(1) Condition	Testing Temp, F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
		Bar 1057 - 0.75% Niobium (continued)				
1	as rolled	78	none	86,300	0.5	1.6
		750	-	83,100	19	78.5
		1200	78,000	80,700	17	76.1
		1600	53,400*	72,100	16	72.9
	str. relieved	78	none	83,100	0.5	1.7
		750	74,500*	82,400	19	75.7
		1200	70,800*	78,100	16	76.8
		1600	59,300	69,100	18.5	71.0
	recrystallized (2300 F)	80	55,800	73,400	15.5	13.5
		750	15,200	43,400	53	83.8
		1200	13,800	38,700	47.5	85.1
		1600	-	35,100	49	83.7
		Bar 1048 - 0.69% Ti, 0.12% R.E.				
5/8	as rolled	80	91,000*	110,100	22	38.5
		750	66,200*	84,200	20	52.3
		1200	59,800*	73,800	18	82.3
		1600	47,500*	60,300	17	77.3
	str. relieved	80	82,400*	108,300	34	46.1
		750	61,500*	78,100	19	73.8
		1200	62,000*	69,400	18	81.5
		1600	-	60,700	17	76.6
	recrystallized (2500 F)	80	53,700	68,400	8	6.3
		750	16,900	38,300	67	81.6
		1200	11,400	34,700	65	84.9
		1600	13,400*	33,800	41	84.8
		Bar 1009 - 1.26% Titanium				
5/8	as rolled	78	109,000*	124,200	4	1.6
		750	87,200*	92,600	19	97.9
		1200	64,900*	80,900	18	80.2
		1600	56,600*	69,100	20	82.2
	str. relieved	78	106,300*	125,500	20	24.6
		750	85,500*	95,500	18	77.8
		1200	71,000*	81,000	18	76.8
		1600	65,900	68,400	14	40.2

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature

(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars

* 0.1% offset yield strength taken from stress-strain plot; all other yield strength values from drop in load

TABLE 3 (continued)

Bar Dia In.	(1) Condition	Testing Temp, F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
		Bar 1009 - 1.25% Titanium (continued)				
5/8	recrystallized (2900 F)	78	61,400	80,800	19	25.3
		750	33,100	44,000	55	76.3
		1200	22,800	43,300	42	91.7
		1600	14,900*	45,900	29	40.7
		Bar 1051 - 0.54% Vanadium				
5/8	as rolled	78	90,300*	104,400	40	71.0
		750	37,900*	81,000	18	79.0
		1200	-	76,900	20	72.7
		1600	-	60,900	15	72.5
	str. relieved	78	93,400	103,600	38	72.2
		750	41,400*	79,100	19	78.6
		1200	35,800	75,000	18	76.9
		1600	45,700*	60,800	21	75.4
	recrystallized (2100 F)	78	70,400	74,400	40	37.1
		750	41,400	45,500	55	81.6
		1200	26,300	45,500	40	83.6
		1600	13,300	32,400	52	79.8
1	as rolled	78	95,300	100,000	4	2.3
		750	75,200	76,100	15.5	78.3
		1200	-	73,900	16.5	75.1
		1600	48,600*	57,600	20	78.5
	str. relieved	78	85,100	92,200	3.5	4.0
		750	65,900	72,700	19	76.8
		1200	64,300*	68,200	17	75.3
		1600	-	50,300	17	88.9
	recrystallized (2500 F)	80	56,300	69,700	20.5	18.1
		750	16,700	42,200	50	80
		1200	19,700	41,800	32	86.8
		1600	13,300	32,500	50	86.9
		Bar 1012 - 0.56% Vanadium				
5/8	as rolled	78	98,000*	121,500	4	7.4
		720	81,200*	102,000	16	65.5
		1200	56,800*	90,100	18	73.1
		1600	44,800*	70,100	21	79.9

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature

(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars

* 0.1% offset yield strength taken from stress strain plot; all other yield strength values from drop in load

TABLE 3 (continued)

Bar Dia In.	(1) Condition	Testing Temp, F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
		Bar 1012 - 0.56% Vanadium (continued)				
5/8	str. relieved	78	76,600	122,200	26	39.2
		750	65,600*	90,600	9	69.6
		1200	-	83,000	16	74.5
		1600	60,200	65,400	23	75.9
	recrystallized (2150 F)	78	83,200	83,200	25	20.4
		750	34,700	45,900	53	79.9
		1200	24,200	45,400	39	80.2
		1600	14,400	33,100	41	78.0
1	as rolled	78	87,900	96,000	1	1.7
		750	72,300*	81,000	13	56.5
		1200	70,300*	75,600	16	75.7
		1600	-	59,600	19	80.2
	str. relieved	78	88,300	92,400	1.5	1.1
		750	67,800*	75,900	15	72.9
		1200	60,000*	71,900	16.5	78.7
		1600	55,500*	67,700	18.5	83.0
	recrystallized (2200 F)	79	61,900	70,600	19	15.9
		750	22,000	41,300	56.5	82.7
		1200	15,300	43,500	34	85.0
		1600	15,900	29,700	51	85.9
		Bar 1049 - 0.85% V, 0.003% Ce, 0.003% R.E.				
5/8	as rolled	80	87,900*	112,500	16	24.6
		750	67,000*	90,500	15	71.9
		1200	67,400*	78,300	19	81.5
		1600	34,200*	62,600	19	76.7
	str. relieved	80	79,400*	106,200	2	2.4
		750	66,600*	85,200	17	71.8
		1200	62,100*	75,900	19	77.7
		1600	48,800*	63,100	21	81.7
	recrystallized (2500 F)	80	53,700	53,700	1	0
		750	23,300	39,900	57	83.1
		1200	16,300	38,700	44	82.8
		1600	11,600*	30,100	13	14.9

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature
(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars
* 0.1% offset yield strength taken from stress-strain plot; all other yield strength values from drop in load

TABLE 3 (continued)

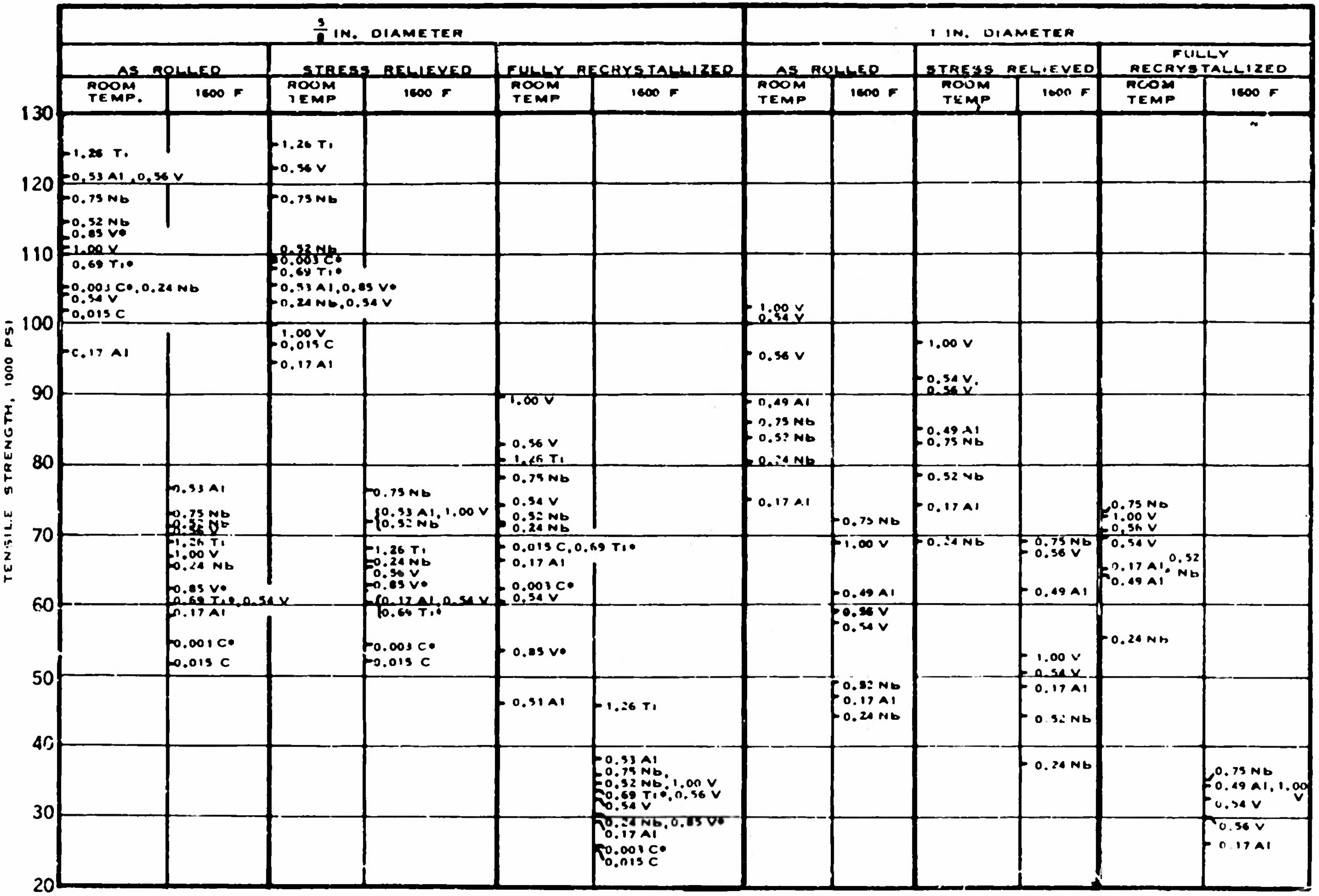
Bar Dia In.	(1) Condition	Testing Temp, F	Yield Str. psi	Tensile Strength psi	(2) Elongation %	Reduction of Area %
		Bar 1052 - 1.00 % Vanadium				
5/8	as rolled	78	98,600	111,200	32	57.8
		750	72,200*	89,300	34	78.2
		1200	71,600*	86,400	15	69.5
		1600	-	67,200	18	74.0
	str. relieved	78	95,200	100,000	29	54.5
		750	68,500*	88,900	13	66.4
		1200	55,200	85,400	15	67.5
		1600	47,700*	71,900	20	74.8
	recrystallized (2150 F)	80	89,700	89,700	28	21.6
		750	39,500	50,000	55	81.6
		1200	37,000	52,200	35.5	79.3
		1600	14,600	35,500	58	83.6
1	as rolled	78	95,400	102,600	2	2.2
		750	84,500	87,000	16	73.4
		1200	79,700*	85,500	13.5	69.1
		1600	-	69,200	20	77.5
	str. relieved	78	93,000	97,200	1.5	2.2
		750	76,600*	81,800	16.5	71.8
		1200	-	80,700	14.5	69.1
		1600	51,900	52,900	17	12.9
	recrystallized (2350 F)	80	70,200	72,900	24	20.8
		750	35,000	46,100	45	80.4
		1200	22,500	49,600	30	73.6
		1600	10,600	33,900	43	88.0

(1) Stress relieved by heating 1 hr at 1800 F, fully recrystallized by heating 1 hr at the indicated temperature
(2) Percent elongation in 1 in. for specimens from 5/8 in. dia bars
Percent elongation in 2 in. for specimens from 1 in. dia bars

* 0.1% offset yield strength taken from stress-strain plot; all other yield strength values from drop in load

CLIMAX MOLYBDENUM CO. 331

JUNE 4, 1951



*DEOXIDIZED WIT RARE EARTH METALS

FIGURE 41 — COMPILATION OF TENSILE STRENGTHS OF UNALLOYED MOLYBDENUM AND SOME MOLYBDENUM-BASE ALLOYS

The 0.75% niobium alloy exhibited excellent strength at 1600 F. Like aluminum, niobium exerts more influence on the strength of molybdenum at elevated temperatures than at room temperature.

Of all the molybdenum and molybdenum-base alloys tested to date, the 1.26% titanium alloy in the form of 5/8" round exhibited the highest room temperature strength in both the as-rolled and the stress-relieved conditions. In the fully recrystallized condition it was somewhat weaker than the 1% vanadium alloy. In the 1" round, the 1% vanadium alloy exhibited the highest strength at room temperature in the as-rolled and stress-relieved conditions and, for all practical purposes, in the fully recrystallized condition as well. The 1.26% titanium alloy has not been tested in 1" round.

In general, the alloys with the highest short-time tensile strengths at 1600 F exhibited the best life in the long-time stress-rupture test. An exception was the 0.53% aluminum alloy in 5/8" round. Although among the stronger alloys at 1600 F in the short-time tensile test, it was among the weaker alloys in the stress-rupture test.

In the as-rolled and stress-relieved conditions, unalloyed molybdenum deoxidized with rare earth metals (1045) was generally slightly stronger than molybdenum deoxidized with carbon (937). The 0.85% vanadium alloy deoxidized with rare earth metals was somewhat lower in strength than an alloy of similar vanadium content deoxidized with carbon. As a group, the alloys deoxidized with rare earth metals were of low strength at room temperature after recrystallization.

Stress-Rupture Properties

Stress-rupture tests on five alloys of the present series were conducted at Battelle Memorial Institute. The tests were made at 1600, 1800, and 2000 F in vacuum upon alloys in the stress-relieved and recrystallized conditions. The data obtained from these tests are given in Table 4 and plotted in Figures 42-44.

Two alloys of the group were outstanding at all three testing temperatures: the 0.75% niobium and the 1.26% titanium alloys. In the stress-relieved condition the niobium alloy had greater stress-rupture life than any other molybdenum-base alloy tested to date. The strengths for 100-hour life (68,000 psi at 1600 F, 53,000 psi at 1800 F, and 22,000 psi at 2000 F) are indeed remarkable. At the end of 425 and 140 hours in the tests at 1600 and 1800 F, respectively, the slope of the stress-rupture curve had not changed, indicating that little or no recrystallization had occurred.

In the fully recrystallized condition, the 1.26% titanium alloy had higher stress-rupture strength at all three temperatures than any other fully recrystallized molybdenum-base alloy so far tested. The very low creep rates of the 0.75% niobium and 1.26% titanium alloys at low test loads is significant. These two alloys had excellent strength and ductility, not only at elevated temperatures but also at room temperature.

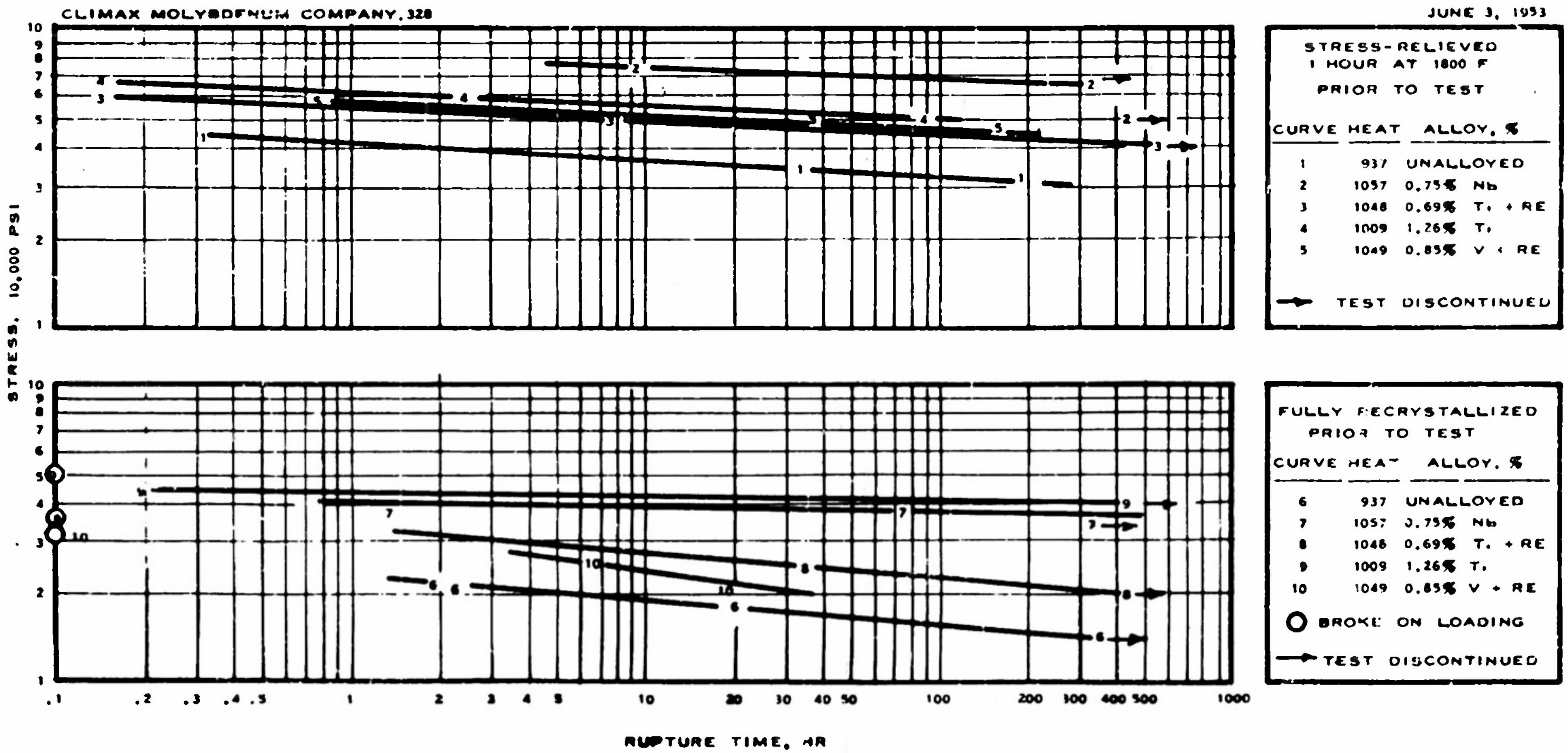


FIGURE 42 — CREEP-RUPTURE STRENGTH OF MOLYBDENUM-BASE ALLOYS TESTED IN VACUUM AT 1600 F IN RECRYSTALLIZED AND STRESS-RELIEVED CONDITIONS

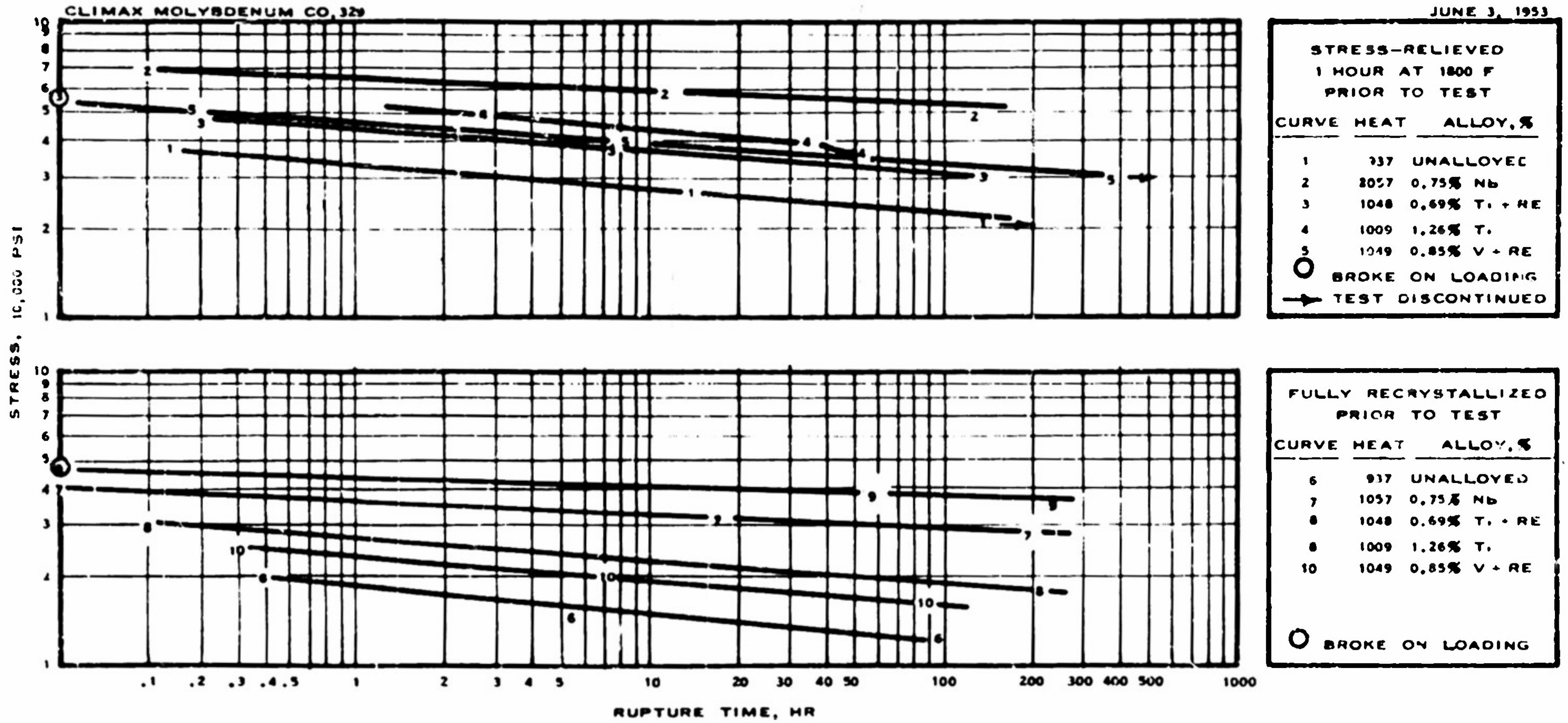


FIGURE 43 - CREEP-RUPTURE STRENGTH OF MOLYBDENUM-BASE ALLOYS TESTED IN VACUUM AT 1800 F IN RECRYSTALLIZED AND STRESS-RELIEVED CONDITIONS

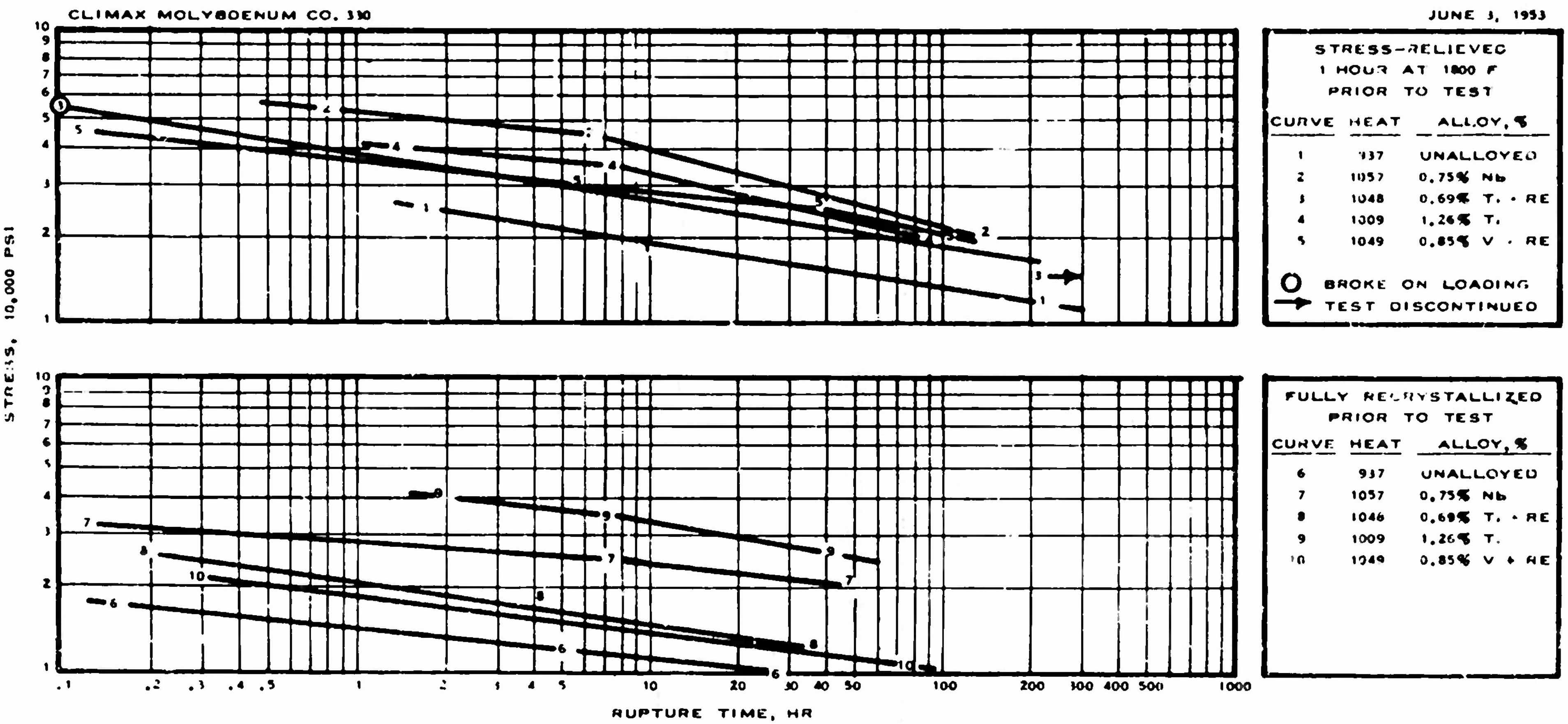


FIGURE 44 – CREEP-RUPTURE STRENGTH OF MOLYBDENUM-BASE ALLOYS TESTED IN VACUUM AT 2000 F IN RECRYSTALLIZED AND STRESS-RELIEVED CONDITIONS

TABLE 4

CREEP RUPTURE DATA ON ARC-CAST MOLYBDENUM-BASE ALLOYS
IN STRESS-RELIEVED AND RECRYSTALLIZED CONDITIONS
AT 1600, 1800 AND 2000 F

Creep Rupture Testing was Conducted by Battelle Memorial Institute

Heat No.	Alloy, %	Heat Treatment	Stress psi	Rupture Time Hours	Elongation %	Reduction of Area, %	Creep Rate %/Hour
				1600 F TEST TEMPERATURE			
937	0.015 C	SR	45,000	0.3	17.4	92.0	-
		SR	37,500	8.0	17.8	92.9	1.7
		SR	30,000	206.4	18.0	93.4	0.012
		R_{2150}	22,300	2.0	54.9	.0	12.2
		R_{2150}	22,000	2.2	64.2	93.1	10.5
		R_{2150}	17,500	19.7	40.7	86.5	0.95
		R_{2150}	14,000	353.5 (a)	34.2	-	0.067
1057	0.75 Nb	SR	75,000	9.5	14.8	75.5	0.31
		SR	65,000	377.2 (a)	3.2	-	0.0058
		SR	50,000	424.9 (a)	0.8	-	0.0006
		R_{2250}	40,000	1.4	43.2	89.4	-
		R_{2250}	37,500	76.4	47.3	46.3	0.12
		R_{2250}	32,800	341.6 (a)	13.9	-	0.004
1048	0.003 C	SR	60,000	0.15	12.1	90.5	-
	0.12 rare	SR	50,000	7.6	13.6	78.4	0.21
	earth metal	SR	40,000	547.6 (a)	2.4	-	0.0017
	0.69 Ti	R_{2500}	35,000	on loading	34.7	82.2	-
		R_{2500}	25,000	35.1	25.2	28.3	0.09
		R_{2500}	20,000	411.9 (a)	4.1	-	0.0023
1009	1.26 Ti	SR	67,000	0.15	15.0	95.0	-
		SR	60,000	2.5	15.8	95.7	0.53
		SR	50,000	91.0	22.2	91.4	0.048
		R_{2900}	44,500	0.2	29.6	95.9	-
		R_{2900}	40,000	472.6 (a)	4.8	-	nil
		R_{2900}	30,000	258.6 (a)(b)	-	-	nil
		R_{2900}	50,000	on loading	28.6	95.8	-

(a) Discontinued (b) Reloaded at a stress of 50,000 psi and failed when the load was applied
SR - Stress relieved one hour
R - Recrystallized, held one hour at indicated temperature

TABLE 4 (continued)

Heat No.	Alloy, %	Heat Treatment	Stress psi	Rupture Time Hours	Elongation %	Reduction of Area, %	Creep Rate %/Hour
			1600 F TEST TEMPERATURE (continued)				
1049	0.001 C	SR	60,000	0.3	13.7	74.4	1.3
	0.003 Ce	SR	50,000	36.1	18.5	86.0	0.11
	0.003 other	SR	45,000	158.0	20.8	89.7	0.027
	rare earth	R_{2500}	32,500	0.05	20.0	31.8	-
	metals	R_{2500}	25,000	6.6	17.6	34.1	1.15
	0.85 V	R_{2500}	20,000	18.9	4.8	6.6	0.18
			1800 F TEST TEMPERATURE				
937	0.015 C	SR	37,500	0.25	14.9	94.0	-
		SR	27,500	13.6	17.1	91.0	-
		SR	21,000	144.8 (b)	4.9	-	0.036
		R_{2150}	20,000	0.5	43.8	95.7	-
		R_{2150}	15,000	5.5	54.4	94.5	7.0
		R_{2150}	12,000	93.3	75.2	93.2	0.28
1057	0.75 Nb	SR	70,000	0.2	12.5	86.2	-
		SR	60,000	11.9	15.8	84.5	0.33
		SR	50,000	140.5	15.6	82.7	0.03
		R_{2250}	40,000	2 min.	47.6	90.4	-
		R_{2250}	32,500	17.7	48.8	80.5	1.35
		R_{2250}	27,500	200.2	37.0	86.1	0.048
1048	0.003 C	SR	55,000	1/2 min.	13.0	89.8	-
	0.12 rare	SR	40,000	7.8	14.5	88.3	0.32
	earth metal	SR	30,000	142.1	17.9	95.0	0.027
	0.69 Ti	R_{2500}	30,000	0.2	36.0	95.2	-
		R_{2500}	22,500	12.4	38.9	93.7	0.62
		R_{2500}	17,500	209.5	41.9	80.8	0.016

(b) Test discontinued because of furnace failure
SR - Stress relieved one hour
R - Recrystallized, held one hour at indicated temperature

TABLE 4 (continued)

Heat No.	Alloy, %	Heat Treatment	Stress psi	Rupture Time Hours	Elongation %	Reduction of Area, %	Creep Rate %/Hour
			1800 F TEST TEMPERATURE (continued)				
1009	1.26 Ti	SR	50,000	2.7	18.3	94.0	11.0
		SR	40,000	35.9	26.2	92.9	0.15
		SR	35,000	56.7	21.1	92.3	0.089
		R_{2900}	47,000	on loading	38.9	95.4	-
		R_{2900}	40,000	57.9	24.2	94.7	0.02
		R_{2900}	35,000	231.0	17.3	91.4	0.002
1049	0.001 C 0.003 Ce 0.003 other rare earth metals 0.85 V	SR	50,000	0.3	14.4	81.8	-
		SR	40,000	9.5	16.8	83.1	0.41
		SR	30,000	381.1 (a)	5.5	-	0.010
		R_{2500}	25,000	0.4	23.0	36.2	-
		R_{2500}	20,000	7.1	29.1	28.2	0.23
		R_{2500}	16,000	85.6	15.1	39.6	0.11
			2000 F TEST TEMPERATURE				
937	0.015 C	SR	25,000	1.7	19.5	92.3	-
		SR	17,500	10.0 (c)	16.0	33.5	-
		SR	12,000	232.1 (a)	6.4	-	0.023
		R_{2150}	17,500	0.15	60.1	83.1	-
		R_{2150}	12,000	5.3	41.3	63.0	3.0
1057	0.75 Nb	SR	55,000	0.8	19.7	84.9	-
		SR	45,000	6.5	16.8	84.2	0.33
		SR	20,000	139.2	48.0	46.4	0.13
		R_{2250}	32,500	0.12	56.0	88.2	-
		R_{2250}	25,000	7.4	48.4	79.3	0.40
		R_{2250}	20,000	49.9	48.0	72.2	0.46

(a) Discontinued (c) Specimen overheated; rupture time estimated
SR - Stress relieved one hour
R - Recrystallized, held one hour at indicated temperature

TABLE 4 (continued)

Heat No.	Alloy, %	Heat Treatment	Stress psi	Rupture Time Hours	Elongation %	Reduction of Area, %	Creep Rate %/Hour
			2000 F TEST TEMPERATURE (continued)				
1048	0.003 C	SR	55,000	on loading	14.4	87.0	-
	0.12 rare	SR	30,000	5.8	16.8	61.8	0.25
	earth metal	SR	15,000	212.7 (a)	3.2	-	-
	0.69 Ti	R_{2500}	25,000	0.2	34.8	72.3	-
		R_{2500}	17,500	4.3	12.0	45.6	1.05
		R_{2500}	12,000	36.7	3.9	4.6	0.037
1009	1.26 Ti	SR	40,000	1.4	19.5	96.0	1.3
		SR	35,000	7.5	22.6	89.2	0.60
		SR	20,000	93.3	21.6	84.0	0.044
		R_{2900}	40,000	2.0	21.2	87.7	0.75
		R_{2900}	35,000	7.2	22.8	86.1	0.18
		R_{2900}	26,000	41.1	20.0	90.0	0.018
1049	0.001 C	SR	45,000	0.12	15.9	85.1	-
	0.003 Ce	SR	25,000	39.8	18.4	75.0	0.018
	0.003 other	SR	20,000	111.4	13.6	36.6	0.036
	rare earth metals	R_{2500}	20,000	0.5	32.3	28.1	-
	0.85 V	R_{2500}	15,000	5.1	18.5	15.1	1.60
		R_{2500}	12,000	76.2	12.0	15.6	0.030

(a) Discontinued
SR - Stress relieved one hour
R - Recrystallized, held one hour at indicated temperature

The 0.85% vanadium alloy deoxidized with rare earth elements did not exhibit as good stress-rupture life as the 0.87% vanadium alloy deoxidized with carbon (third annual report).

Unalloyed molybdenum was lower in stress-rupture strength than all of the molybdenum-base alloys tested to date in the recrystallized condition at all three testing temperatures. Its strength in the stress-relieved condition when tested at 2000 F compared favorably with some of the lower-strength alloys.

Oxidation Resistance

Oxidation tests were conducted on many of the alloys now available. Samples were subjected to a flowing steam of air in separate chambers at 1750 F. The results are plotted as rate of oxidation versus alloy content in Figure 45.

Niobium and vanadium did not alter materially the rate of oxidation of unalloyed, carbon-deoxidized molybdenum. Titanium apparently accelerated oxidation, while aluminum and cobalt suppressed it. Unalloyed molybdenum deoxidized with rare earth metals oxidized at a retarded rate, but titanium and vanadium alloys deoxidized with rare earth metals oxidized faster than corresponding alloys deoxidized with carbon.

TERNARY MOLYBDENUM-BASE ALLOYS

The object of this phase of the investigation was to conduct a preliminary survey of some ternary alloys of molybdenum to determine which alloys provided the greatest possibility of improving the mechanical properties of molybdenum for service as a structural material at elevated temperatures. The experimental work was planned to determine whether addition of two alloying elements would produce a combination of properties superior to those developed by only one alloying element.

The investigation was started on a series of graded ingots in which the concentration of one alloying element was a constant, arbitrarily selected so that the hardness of the binary alloy at 1600 F would be about 90 VPN, and in which the concentration of a second alloying element was gradually increased from zero to a percentage which would yield an alloy of about 200 VPN at 1600 F. By using a graded ingot, a series of alloys could be obtained from a single heat--alloys that otherwise would require the preparation of many heats involving considerable time, material, and effort.

The mechanical characteristics of the bar melting machine, described in the first annual report, are especially suited to the preparation of such ingots. The graded ingots were divided into small, homogeneous sections which were used for metallographic examination, x-ray diffraction studies, and hardness tests at room and elevated temperatures. The sections were also analyzed chemically, and the results of all tests and examinations were correlated with chemical composition. The aim of these correlations was to indicate the concentrations of alloying elements which warranted more extensive investigation on ternary ingots of uniform concentration.

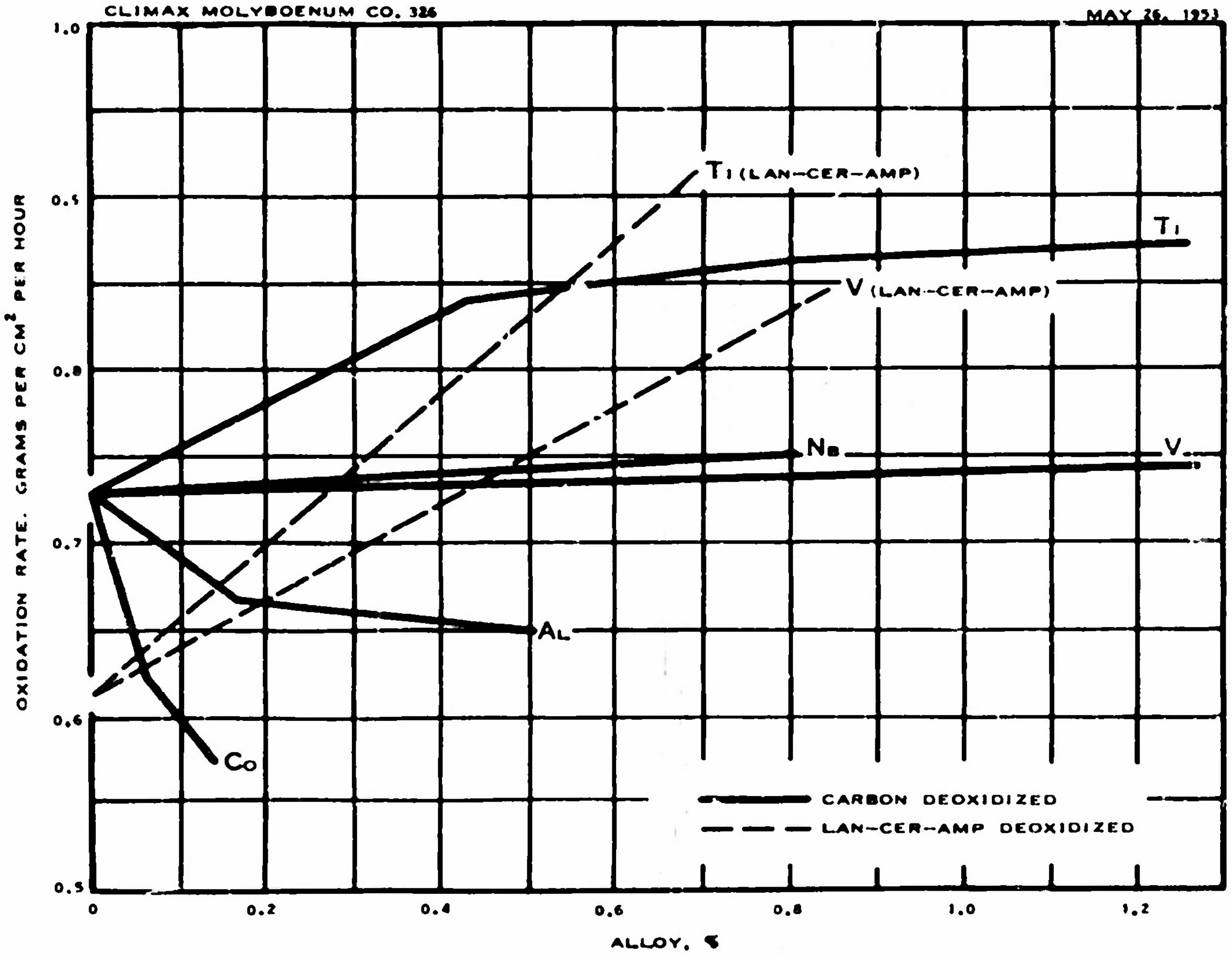


FIGURE 45 – OXIDATION RATES OF SOME MOLYBDENUM-BASE ALLOYS

The first alloys produced in the investigation of ternary systems were alloys of molybdenum and aluminum containing increasing amounts of a third element. A binary molybdenum-aluminum alloy containing 0.17% aluminum (1063) and having a hardness of 90 VPN at 1600 F was selected as the base metal. The third element was added to this base metal in increasing amounts to produce a graded ingot. The binary molybdenum-aluminum alloy was produced according to the schedule given in the second quarterly report (p 57) and was used, in the form of 5/8" diameter bar stock, as the consumable electrode for making the ternary alloys.

Five graded ternary heats have been made, each containing one of the following as the third element: cobalt, niobium, titanium, vanadium, and zirconium. The ternary ingots were made in 2" diameter mold and weighed about six pounds each. The concentration of the third element varied from zero at the bottom of the ingot to a maximum at the top. After casting, the ingots were homogenized at 3000 F for two or three hours in hydrogen atmosphere and slowly cooled. For examination the ingots were split longitudinally. Hardness surveys were made at room temperature, at 1/4" intervals over the entire longitudinal section. The hardness patterns indicated that there was no gross segregation of the alloys; except for a hard outer shell, 1/4" thick, the hardness was uniform across the ingots at any one point on the longitudinal axis.

A core 3/4" square was taken from the ingot for testing. This core was quartered lengthwise and one piece was reserved for determination of hardness at room and elevated temperatures. Another piece was used for chemical analysis, x-ray studies, and metallographic examination, care being taken to identify each sample by its position in the ingot so that the properties could be correlated with chemical composition. The data were plotted against distance on the longitudinal axis and then replotted against composition. The filings for x-ray studies were processed in the manner described in the first annual report.

<u>Mo-Al-Co Alloys</u> (B181)

The macrostructure, hardness, and lattice parameter data obtained from the Mo-Al-Co graded ingot are given in Figure 46. Only the lower half of the ingot was used, because, as is evident in the macrostructure, a crater occupied the upper portion of the ingot. The hardness of these alloys was somewhat greater than that of comparable binary molybdenum-cobalt alloys (cf. Figure 32, second quarterly report), especially at 1600 F. Since both aluminum and cobalt contract the lattice parameter of molybdenum, their combined effect was also to contract the lattice parameter. From the data at hand, the effect appeared to be additive, but no quantitative determination could be made.

The microstructure of the alloy containing 0.15% cobalt is shown in Figure 51. The coring shown in the photomicrograph is evidence that three hours at 3000 F was insufficient for homogenization. The microporosity that appears at 100X seems to be closely related to the dendritic interstices. No second phase was found in the alloy concentrations covered in the graded heat. By chemical analysis it was determined that about 0.05% of the aluminum was present in the form of aluminum oxide. This suggests that some of the fine particles in the figure at 1000X were not voids but rather aluminum oxide. The presence of both voids and oxide was confirmed metallographically.

Mo-Al-Nb Alloys (B179)

The lattice parameter, hardness, and macrostructure of the graded heat containing niobium are shown in Figure 47. The data were obtained upon the portion of the ingot below the crater. The lattice parameter increased with increasing niobium content, but not as much as in the molybdenum-niobium binary alloys, indicating the effect of aluminum in contracting the lattice parameter. With regard to hardness, the softening effect of aluminum on room temperature hardness was evident in the alloys containing less than 0.3% niobium. The hardness of the alloys containing more than 0.3% niobium was comparable to that of binary molybdenum-niobium alloys. At 500 and 1600 F the hardness of the ternary alloys was appreciably higher than for corresponding molybdenum-niobium alloys (Figure 31, second quarterly report). For all practical purposes there was no change in hardness of the ternary alloys from 500 to 1600 F.

The microstructure of the alloy containing 0.5% niobium is shown in Figure 52. A small amount of coring and interdendritic porosity can be observed in the photomicrographs.

Mo-Al-Ti Alloys (B177)

The hardness and macrostructure of the graded heat containing titanium are shown in Figure 48. During casting of the lower portion of the ingot (0-2.5% titanium) it was difficult to control the arc; therefore, this portion of the ingot was defective and was not used for determination of hardness. In the composition range used (2.75-4.25% titanium) there was a small, gradual increase in hardness with increasing titanium content.

The microstructure of the 3% titanium alloy is shown in Figure 53. The interdendritic segregation shown in the figure indicates that two hours at 3000 F was not sufficient for homogenization. The marked coring suggests that there had been a wide temperature range of solidification. At high magnification (not shown) yellowish inclusions, believed to be titanium oxide, were observed on unetched specimens.

Mo-Al-V Alloys (B178)

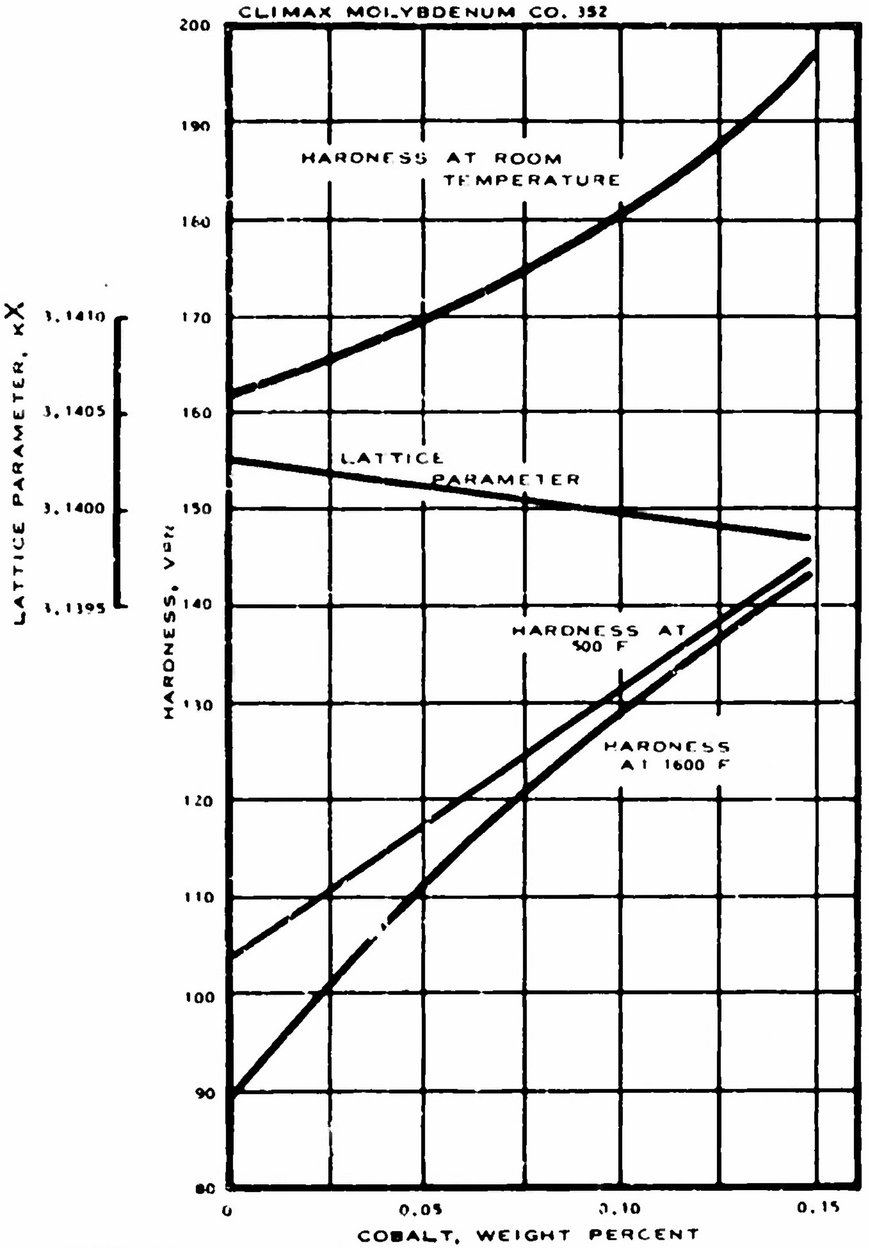
The macrostructure and data on lattice parameter and hardness of the graded heat containing vanadium are shown in Figure 49. Both aluminum and vanadium contract the lattice paramenter of molybdenum. In combination they contracted the lattice slightly more than vanadium alone. The hardness of the graded material at room temperature was appreciably lower than for corresponding binary molybdenum-vanadium alloys. At 500 and 1600 F, however, the hardness of the ternary alloys was appreciably above that of the binary alloys. The hardness-versus-composition curves at 500 and 1600 F practically coincided above 0.8% vanadium, indicating little change in hardness in that temperature range.

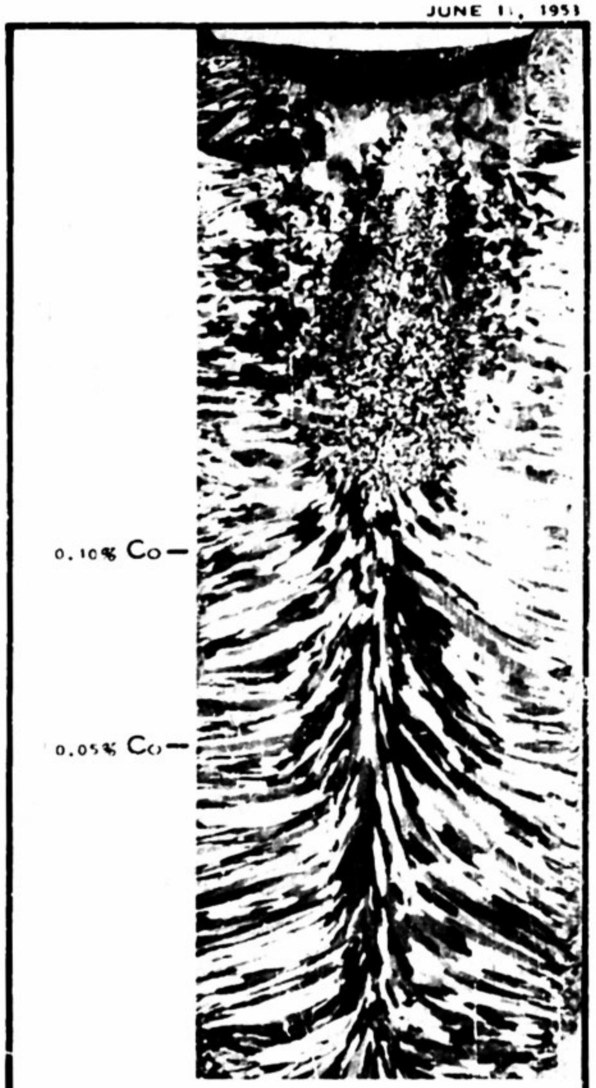
Severe coring in the ternary alloy containing 2% vanadium is shown in Figure 54. Microporosity and aluminum oxide, but no intermetallic second phase, were visible in the structure at 1000X.

Mo-Al-Zr Alloys (B182)

The hardness and macrostructure of the graded heat containing zirconium are shown in Figure 50. The ternary alloys containing up to 0.2% zirconium had the lower hardness at room temperature associated with molybdenum-aluminum alloys without zirconium. At 500 F the hardness of the ternary alloys was slightly higher than for the corresponding molybdenum-zirconium alloys without aluminum. At 1600 F, the Mo-Al-Zr alloys containing up to 0.2% zirconium were harder than the corresponding molybdenum-zirconium alloys, and above 0.2% zirconium the molybdenum-zirconium alloys were harder.

Severe coring and porosity, as well as an interdendritic second phase, were observed in the microstructure, Figure 55, of the ternary alloy containing 0.35% zirconium. The precipitate shown in the photomicrograph at 1000X is similar to that described in the third annual report (Figure 51), which was believed to be an aluminum-zirconium-oxygen compound.



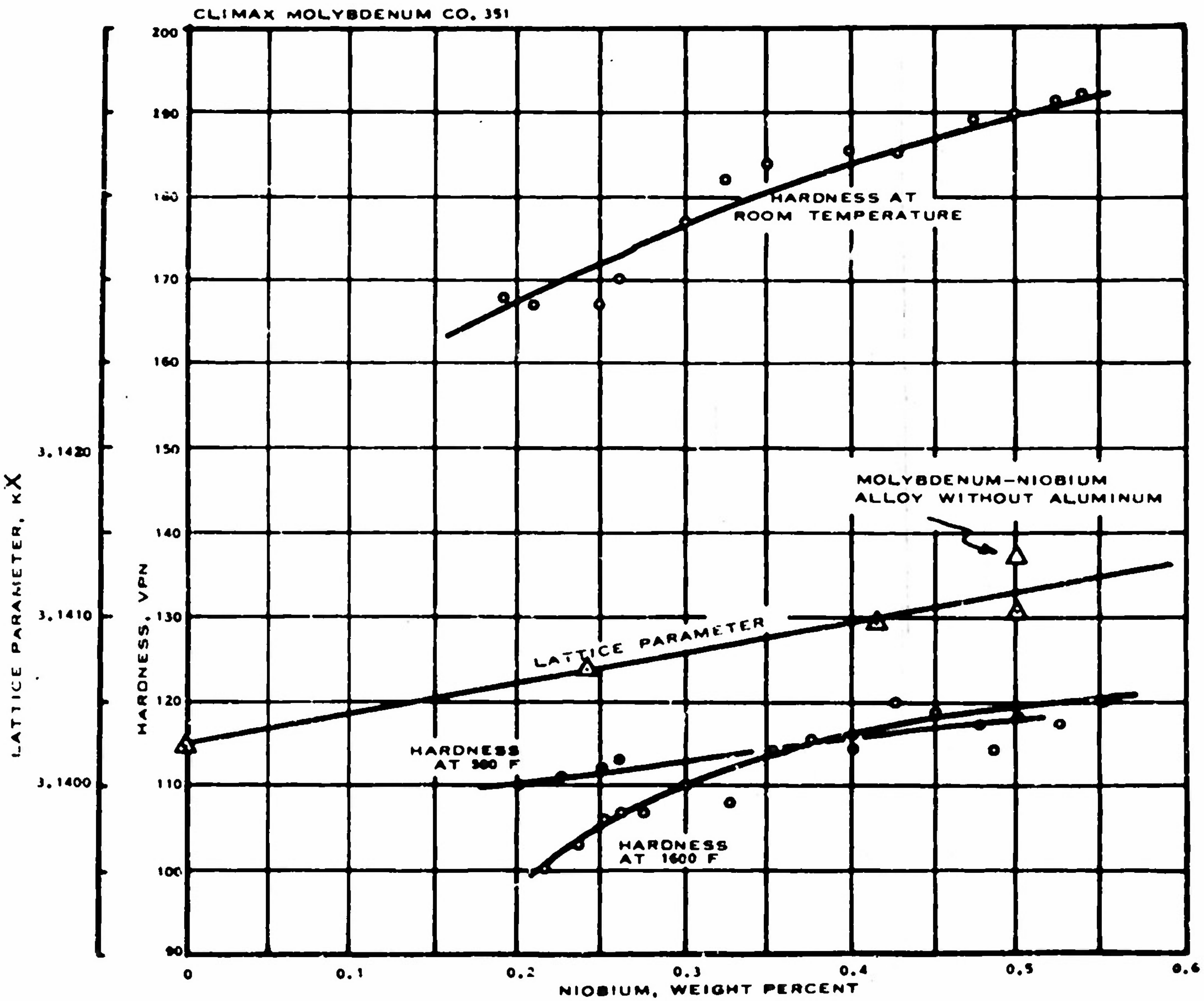


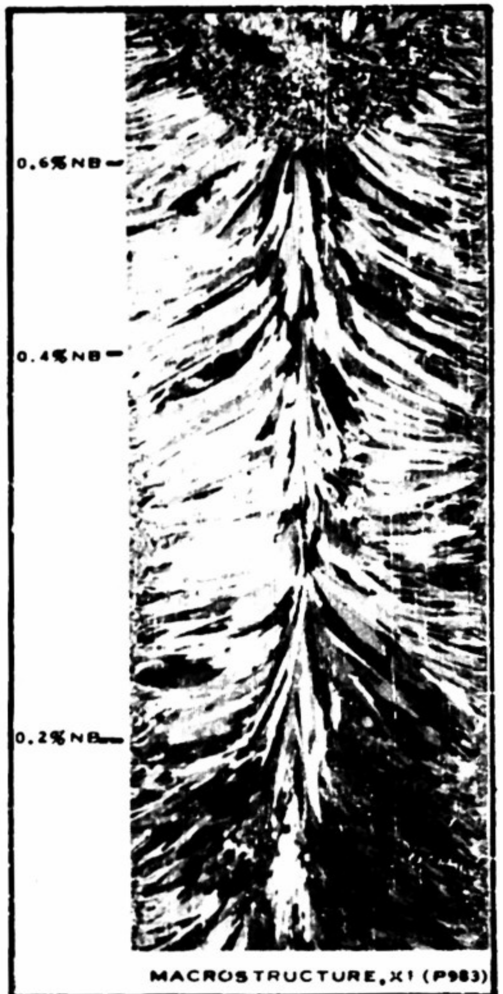
MACROSTRUCTURE, X1 (P-76)

HEAT B181
0.16% ALUMINUM
0-1% COBALT ADDED
BALANCE MOLYBDENUM

CAST IN PURIFIED, RECIRCULATED ARGON IN 2" DIA MOLD. HOMOGENIZED 1 HR AT 3000 F IN HYDROGEN. LOWER HALF OF INGOT USED FOR PROPERTY DETERMINATIONS

FIGURE 46 — HARDNESS, LATTICE PARAMETER, AND MACROSTRUCTURE OF MOLYBDENUM-BASE ALUMINUM-COBALT ALLOYS





HEAT B179

0.16% ALUMINUM
0-5% NIOBIUM ADDED
BALANCE MOLYBDENUM

CAST IN PURIFIED, RECIRCULATED ARGON IN 2" DIA MOLD. HOMOGENIZED 2 HR AT 3000 F IN HYDROGEN.

FIGURE 47 - HARDNESS, LATTICE PARAMETER, AND MACROSTRUCTURE OF MOLYBDENUM-BASE ALUMINUM-NIOBIUM ALLOYS

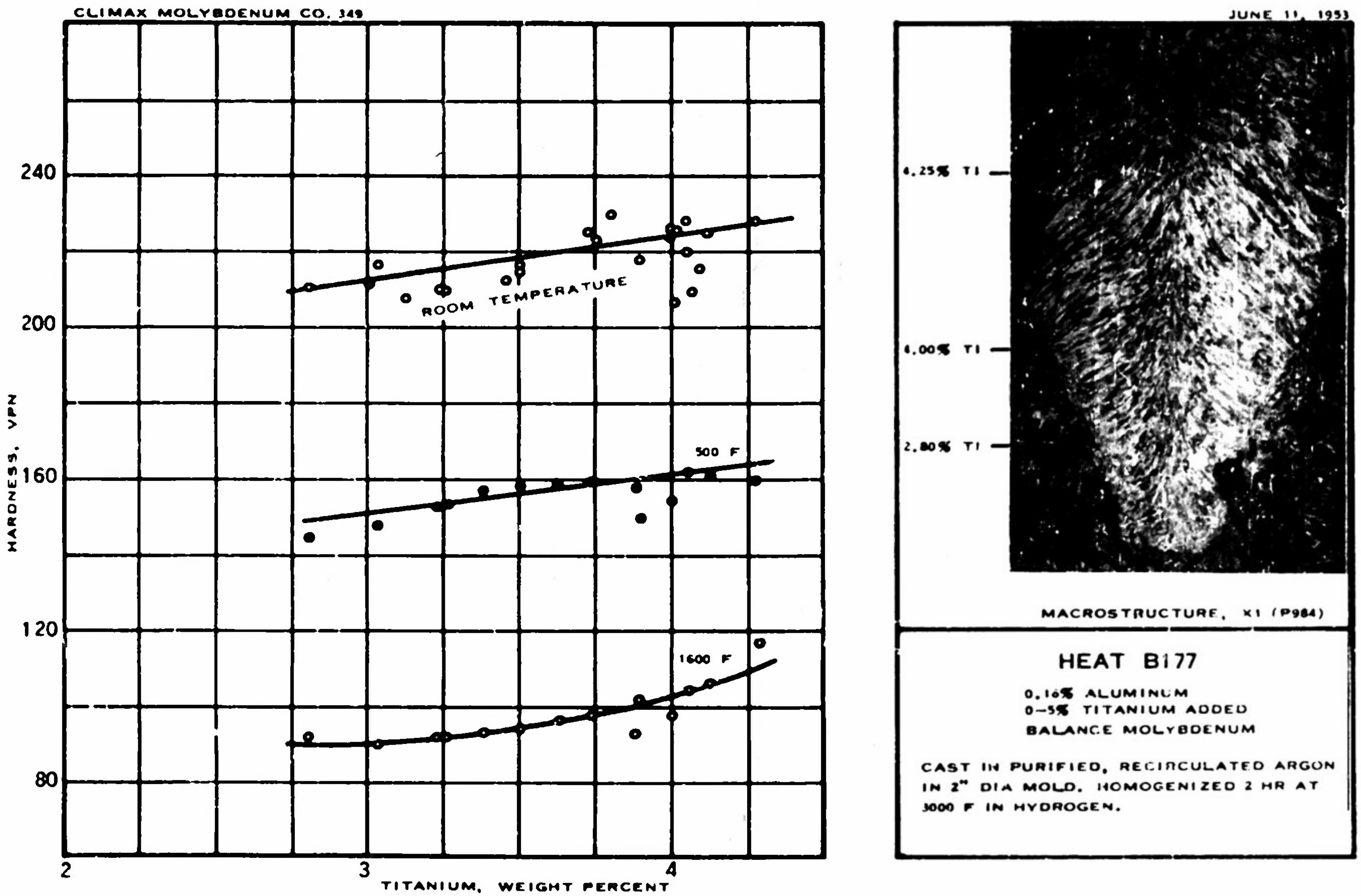
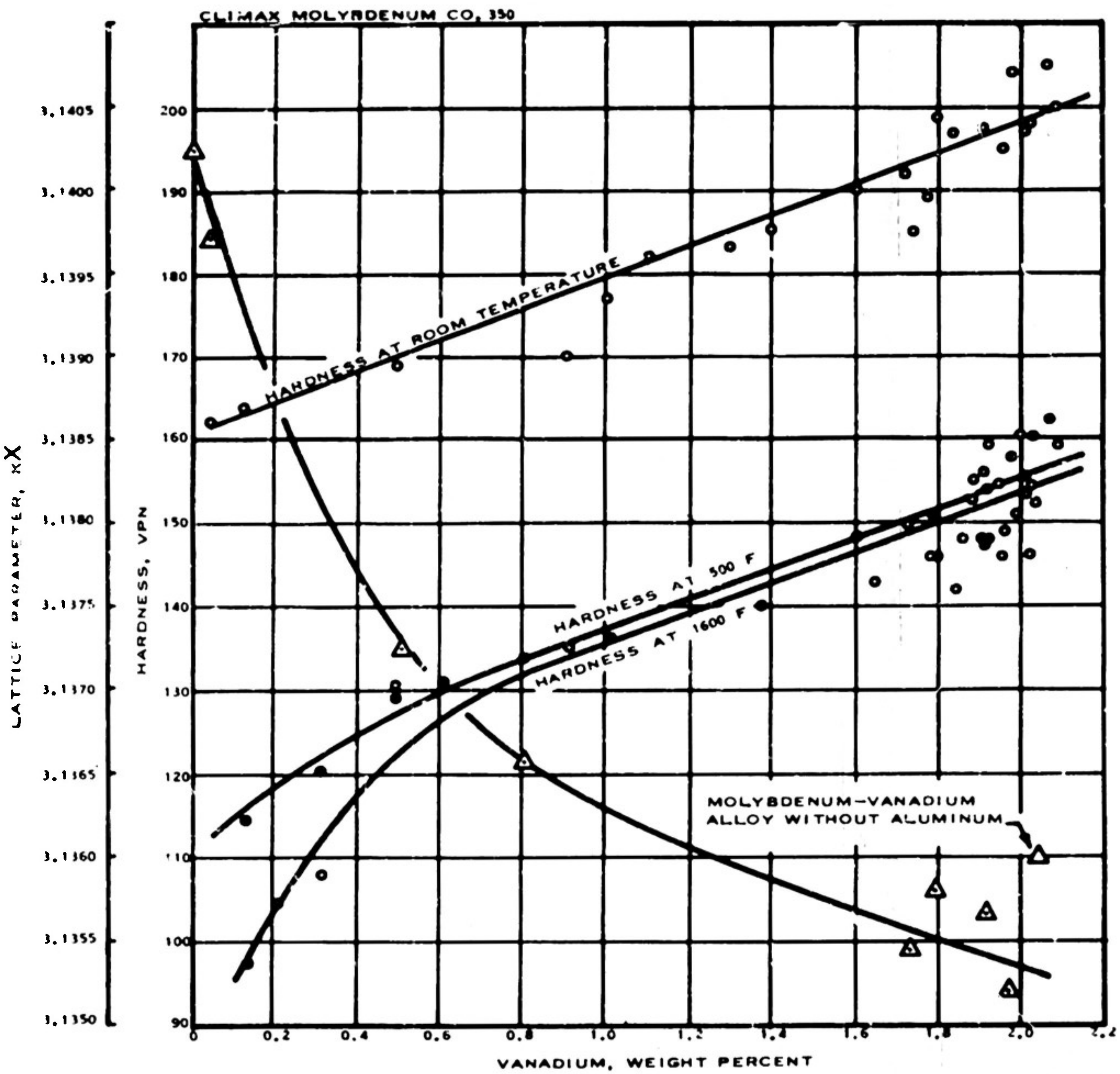
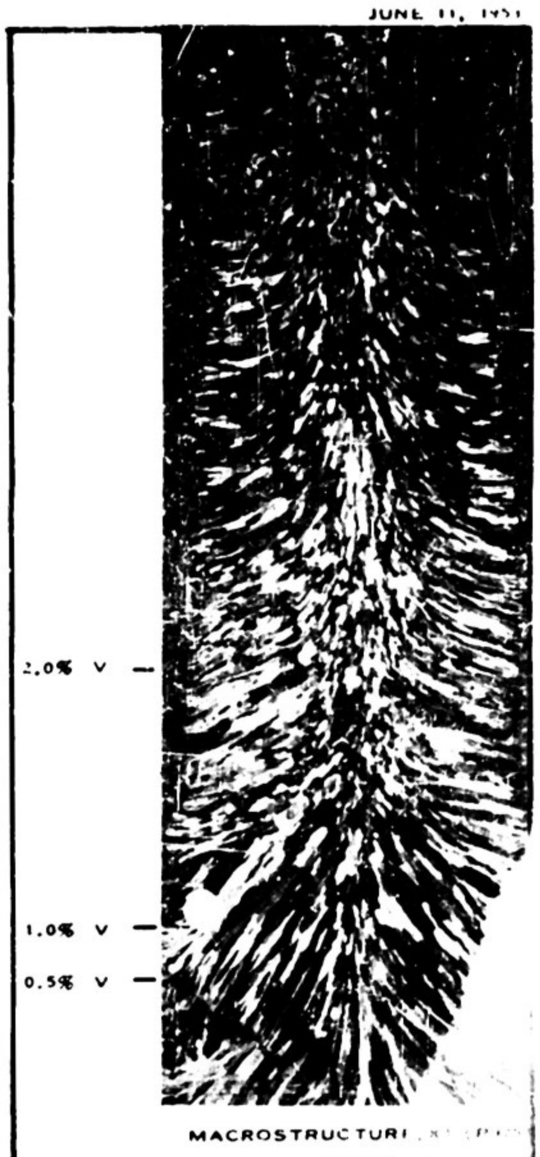


FIGURE 48 – HARDNESS AND MACROSTRUCTURE OF MOLYBDENUM-BASE ALUMINUM-TITANIUM ALLOY





HEAT B178

0.16% ALUMINUM
0-4% VANADIUM ADDED
BALANCE MOLYBDENUM

CAST IN PURIFIED, RECIRCULATED ARGON IN 2" DIA MOLD. HOMOGENIZED 2 HR AT 3000 F IN HYDROGEN.

FIGURE 49 — HARDNESS, LATTICE PARAMETER, AND MACROSTRUCTURE OF MOLYBDENUM-BASE ALUMINUM-VANADIUM ALLOY

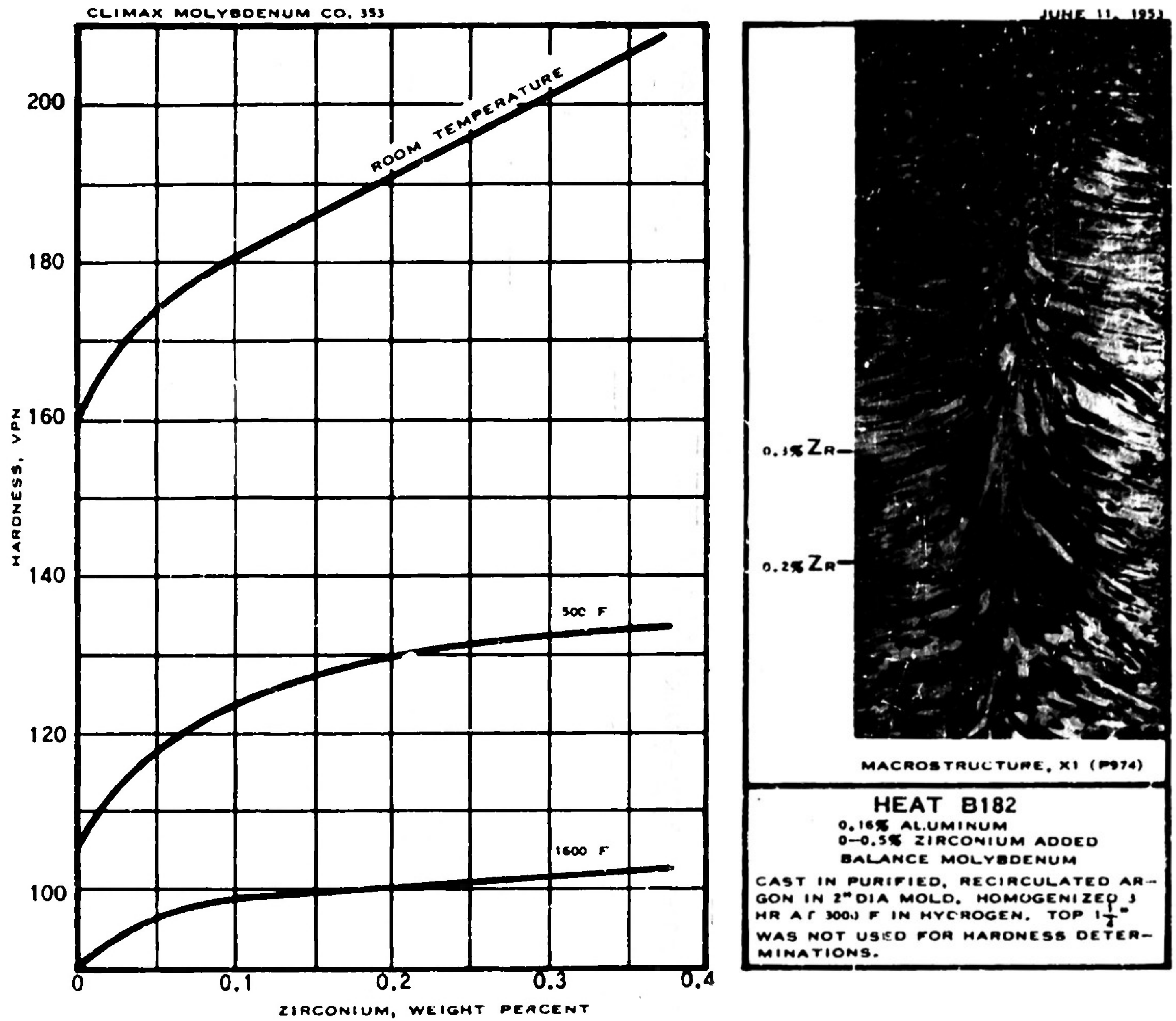
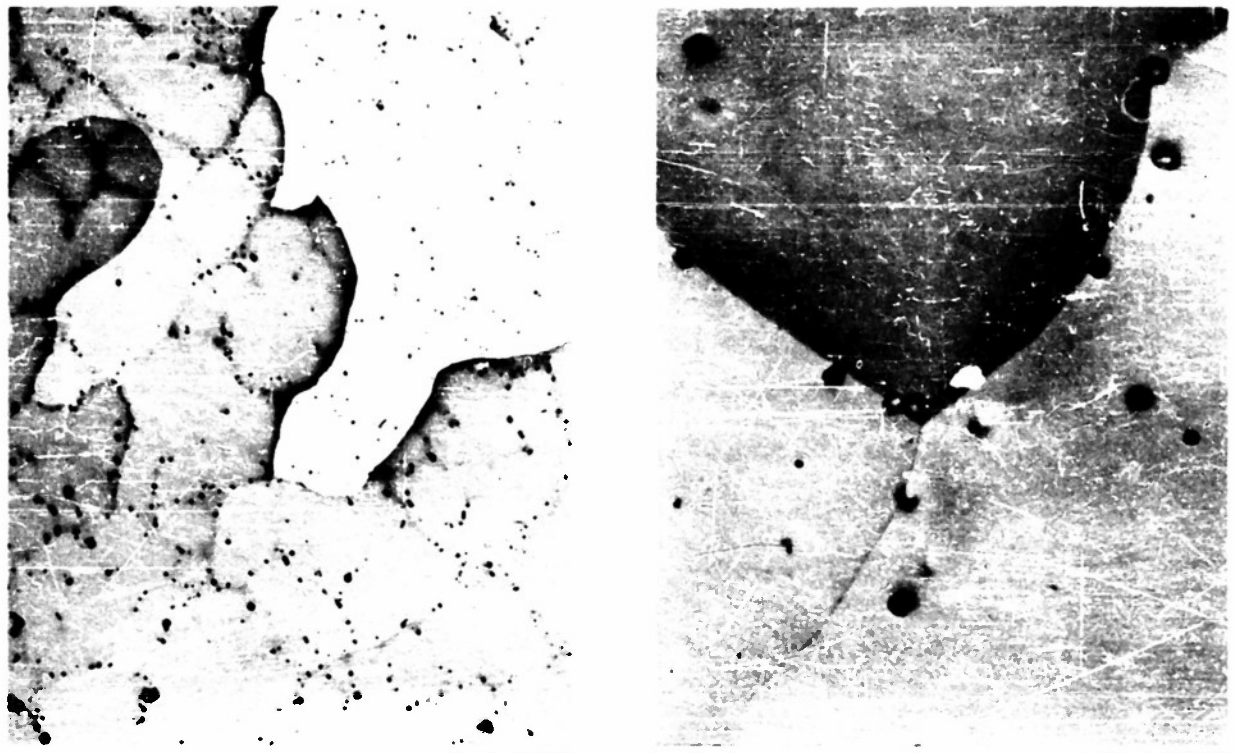


FIGURE 50 – HARDNESS AND MACROSTRUCTURE OF MOLYBDENUM-BASE ALUMINUM-ZIRCONIUM ALLOY

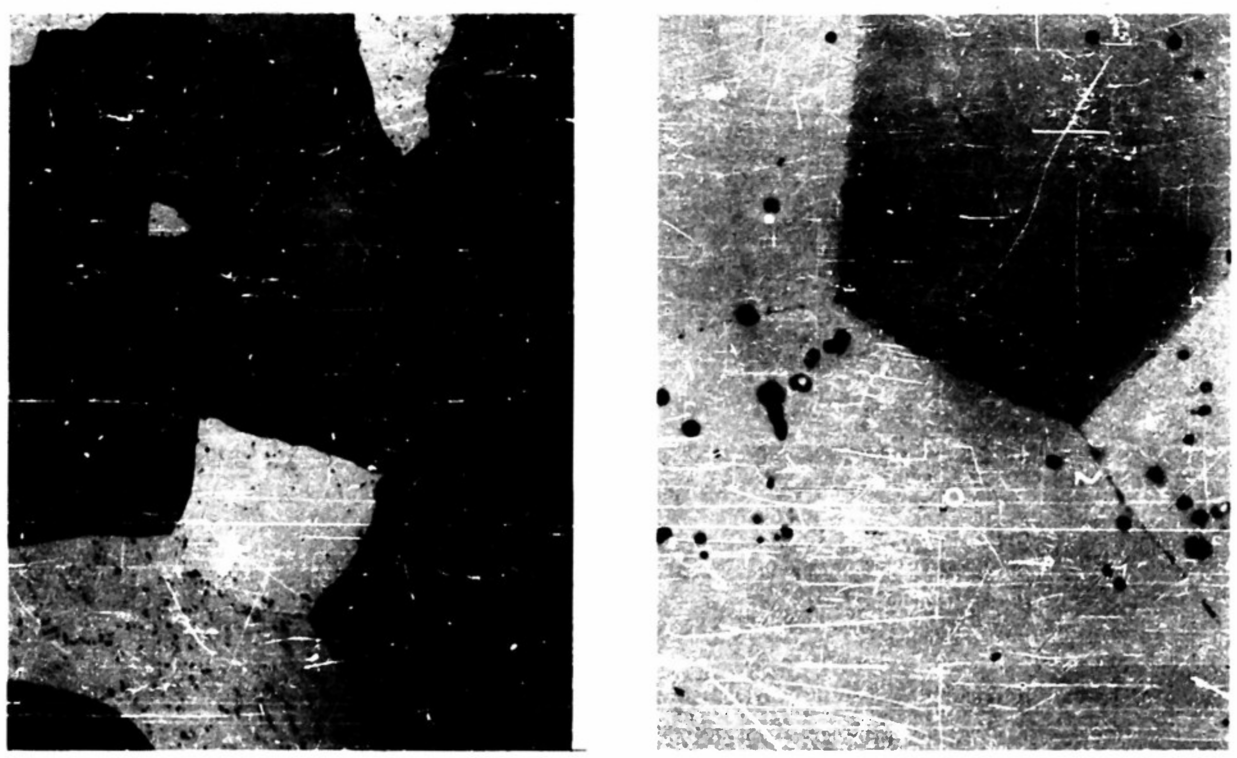


X100 (M2907) X1000 (M2908)

FIGURE 51 — MICROSTRUCTURE OF Mo-Al-Co ALLOY, HEAT B181

0.16% ALUMINUM, 0.15% COBALT, BALANCE MOLYBDENUM, CAST IN ARGON

ELECTROPOLISHED, ETCHED IN SODIUM HYDROXIDE + POTASSIUM FERRICYANIDE SOLUTION



X100 (M2710) X1000 (M2853)

FIGURE 52 — MICROSTRUCTURE OF Mo-Al-Nb ALLOY, HEAT B179

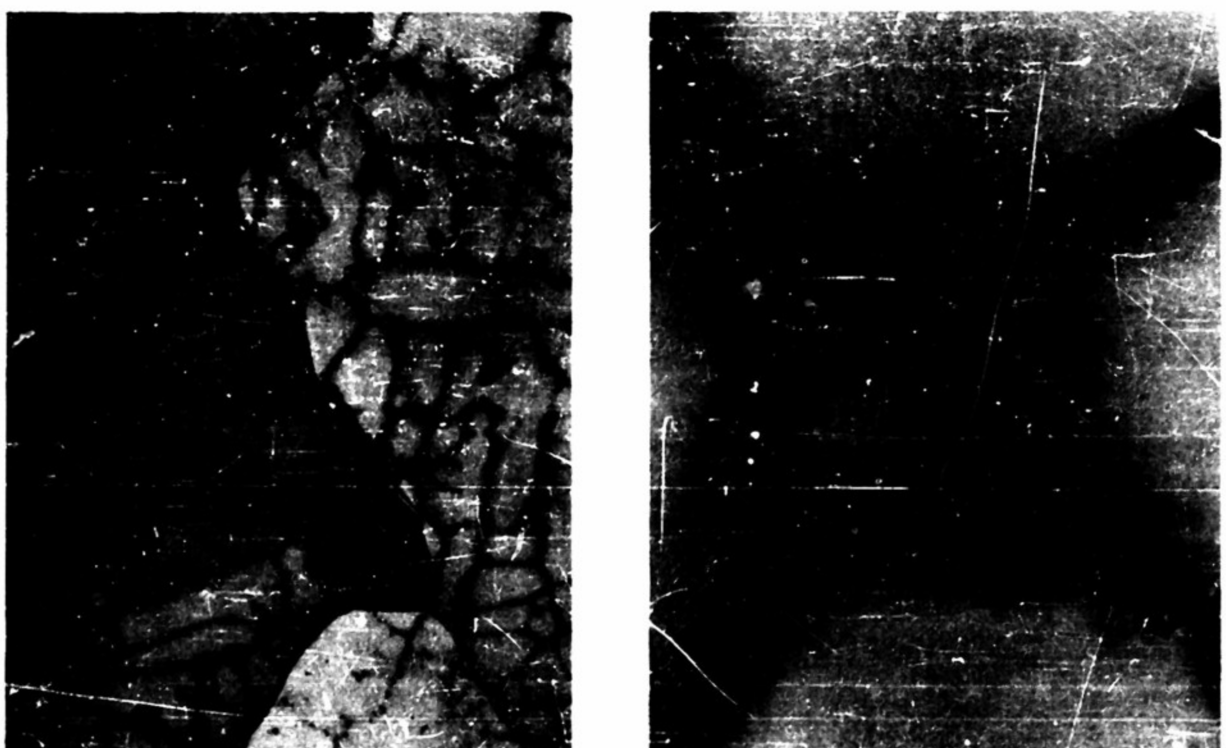
0.16% ALUMINUM, 0.5% NIOBIUM, BALANCE MOLYBDENUM, CAST IN ARGON

ELECTROPOLISHED, ETCHED IN SODIUM HYDROXIDE + POTASSIUM FERRICYANIDE SOLUTION

X100 (M2720) X1000 (M2721)

FIGURE 53 — MICROSTRUCTURE OF Mo-Al-Ti ALLOY, HEAT B177

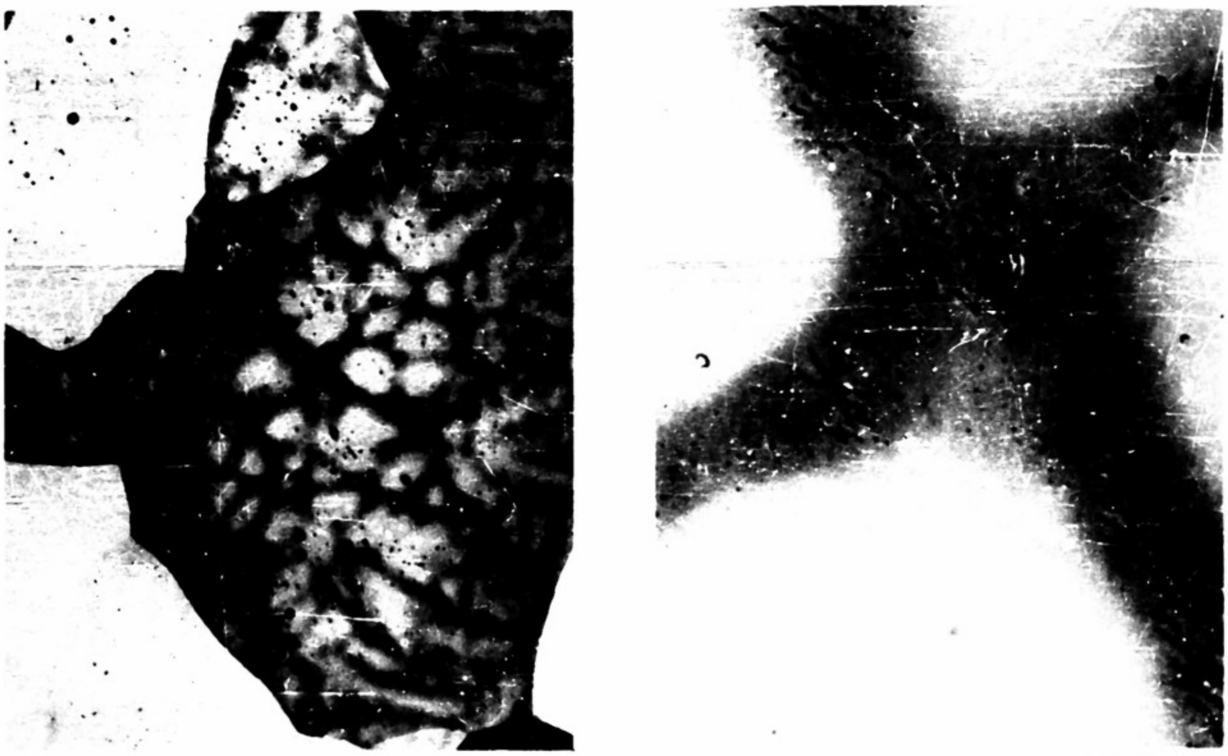
0.13% ALUMINUM, 3% TITANIUM, BALANCE MOLYBDENUM, CAST IN ARGON
ELECTROPOLISHED, ETCHED IN SODIUM HYDROXIDE + POTASSIUM FERRICYANIDE SOLUTION



X100 (M2702) X1000 (M2703)

FIGURE 54 — MICROSTRUCTURE OF Mo-Al-V ALLOY, HEAT B178

0.16% ALUMINUM, 2% VANADIUM, BALANCE MOLYBDENUM, CAST IN ARGON
ELECTROPOLISHED, ETCHED IN SODIUM HYDROXIDE + POTASSIUM FERRICYANIDE SOLUTION



X100 (M2715) X1000 (M2716)

FIGURE 55 — MICROSTRUCTURE OF Mo-Al-Zr ALLOY, HEAT B182

0.16% ALUMINUM, 0.35% ZIRCONIUM, BALANCE MOLYBDENUM, CAST IN ARGON
ELECTROPOLISHED, ETCHED IN SODIUM HYDROXIDE + POTASSIUM FERRICYANIDE SOLUTION